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AN OBJECTIVE METHOD OF FORECASTING WINTERTIME PRECIPITATION IN NORTHEAST COLORADO

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ABSTRACT

General aspects of the problem of forecasting precipitation in northeast Colorado are discussed and the forecast area described. A precipitation day for the area is defined on the basis of the number of cooperative weather stations reporting precipitation. Variables with prognostic value in determining upslope flow and, consequently, precipitation in northeast Colorado, are discussed. To obtain a forecasting method, the variables are combined by graphical correlation techniques. The method is tested on independent data; the results are consistent with those obtained on the original data and show a skill score above chance of 50 percent.

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INTRODUCTION

This study attempts to combine the techniques used in several previous investigations with ideas presented by the forecasters and to apply them to precipitation forecasting for an area. Earlier investigations by Horning [1] and Eberhardt [2] have dealt with forecasting precipitation more for a specific locality than for an area. Others have demonstrated the feasibility of establishing objective methods to be used in precipitation forecasting. This approach does not differ greatly from investigations made by Vernon [3] in forecasting the occurrence of precipitation at San Francisco or by Penn [4] in forecasting precipitation amounts at Boston. The specific problem of this investigation was the forecasting of precipitation from 12 to 36 hours in advance for northeastern Colorado. The objective was to determine the relationship between data taken from the synoptic charts and the probabilityof subsequent precipitation. An effort was made to simplify forecast procedures so the forecaster may by a better evaluation of the synoptic situation place a higher degree of confidence in his forecasts.

The data used in the development of the objective procedures were taken from the 1230 GMT (0530 MST) surface weather charts and the 0300 GMT (2000 MST) 700-mb. charts for the months of January, February, and March for the years 1944, 1946, 1947, and 1948. This gives a total of 362 cases which shall be referred to as dependent or original data. Data for the same months of 1945 and 1949 (180 cases) were reserved to test the procedures and shall be referred to as independent or test data. In addition, data for the months of November and December 1947 and 1948 were utilized to test the applicability of the procedures to those months.

GENERAL ASPECTS OF THE PROBLEM

Several aspects of the problem had to be considered before the development of objective procedures could be

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completed. These include (*a*) the forecast area, (*b*) the forecast period, (*c*) the season of the year, and (*d*) the definition of a precipitation day for the area.

FORECAST AREA

Northeastern Colorado is a natural division of the State from the standpoint of both topography and climate. This area can be described as rolling plains. The elevation rises from approximately 4,000 feet along the eastern boundary to near 6,000 feet at the foothills of the Rocky Mountains. The southern portion of the region is bounded by a ridge of hills known as the Palmer Lake Divide. The elevation of this ridge is about 8,600 feet where it joins the Rockies, but it decreases to near 4,000 feet at the Colorado-Kansas border. Thus, the area is in a rain shadow with storms which produce southerly through northwesterly surface winds over the area. The increase in elevation of the terrain from east to west, however, provides sufficient lift for northerly through southeasterly flow that the resultant cooling may produce precipitation.

FORECAST PERIOD

The forecast that is issued in the morning was chosen for the investigation because it holds the place of paramount importance, its issuance coinciding with the users' operational planning. Another reason considered was the time of observations by the cooperative stations used for precipitation verification. For the most part cooperative observers measure the 24-hour amount of precipitation either in the early morning or in the evening. Only the evening observations were used because they lend themselves better to the periods corresponding to the forecasts. To avoid any overlapping of periods the "today" portion of the official forecast was eliminated. Thus the forecast period of this study is the 24 hours from 1730 MST "today" to 1730 MST "tomorrow." This is the same as the "tonight and tomorrow" portion of the official forecast issued from the 1230 GMT charts. No effort has been made to subdivide the period since there is no adequate means of verifying the results. Consequently, it is left to the forecaster to ascertain, if necessary, in which of the 12-hour periods the precipitation will occur.

SEASON

The variables used in this study are applicable only to those situations which lead to upslope flow at the surface and subsequent widespread precipitation and are not suited for forecasting thunderstorm activity. The procedures developed are therefore applicable only to the winter season, November to March, inclusive. Although they are based on data for January, February, and March, tests on November and December data indicate that they are equally applicable to those months.

DEFINITION OF A PRECIPITATION DAY

The rainfall data from Weather Bureau Cooperative Stations published in the *Monthly Climatological Data*, Colorado Section, served as a basis for determining a precipitation day. In northeast Colorado there are many Cooperative Stations. No station at an elevation above 6,000 feet was used since precipitation might be unduly influenced by the altitude, and no station that reported or measured precipitation at times not corresponding with the forecast period was used. An analysis was made of the number of times each station reported and only those which reported every month were used. Twenty-one stations were thus selected. The distribution of these stations over the area is shown in figure 1. The definition of a precipitation day was then based on a certain percentage of these stations reporting precipitation. The selection of this percentage is an entirely arbitrary decision. It would seem that the value selected should be as low as possible and still assure a spatial distribution such that at least two quadrants of the area are represented by precipitation reports on a "precipitation" day. From the distribution of the 21 stations used (fig. 1) it can be seen that the greatest number in any quadrant of the area is 7 stations. Thus to assure that at least 2 quadrants are represented, at least 8 of the 21 stations should report precipitation. Further, even though 7 or less stations reporting precipitation were distributed over the entire area (which is usually the case) it would represent a squally condition and not a widespread precipitation situation. A precipitation day for the purposes of this paper, then, is any 24-hour period from 1730 MST one day to 1730 MST the following day during which *more* than 33⅓ percent of the stations report precipitation. A trace was considered precipitation.

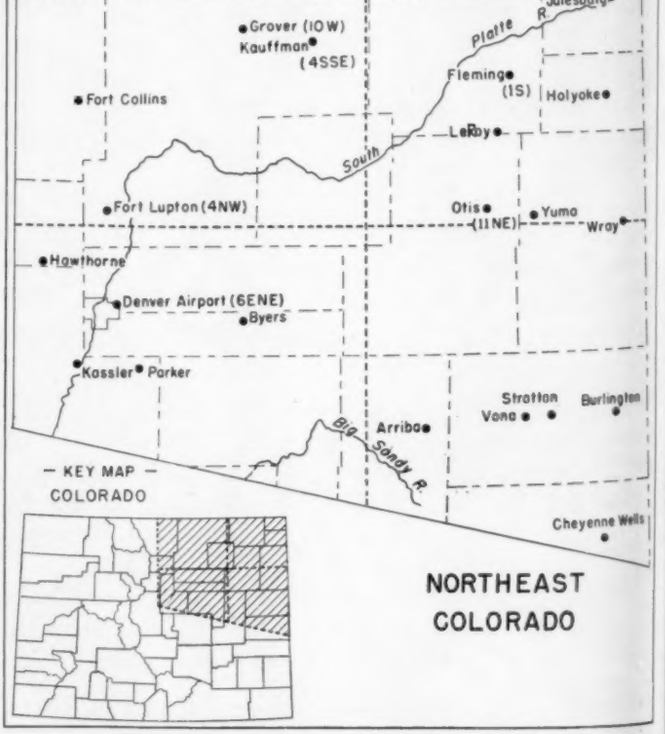


FIGURE 1.—Distribution of Cooperative Stations in northeast Colorado used for verification purposes.

VARIABLES AND PROCEDURES USED

In selecting variables which might be related to the occurrence of widespread precipitation in northeast Colorado, results of previous research and the experience of the Denver forecast staff formed the main sources of ideas.

The underlying principle in selecting most of the variables was to select those which would either precede the establishing of an upslope situation, or indicate the continuance of an upslope situation, and thus be indirectly related to the occurrence of precipitation. A second consideration was to establish some measure of the moisture available for precipitation formation if upslope conditions developed.

The days were stratified first on the basis of whether or not precipitation was occurring in northeast Colorado at the time of the forecast map (1230 GMT). This stratification was based on the a priori reasoning that variables having prognostic value for the beginning of upslope circulation might be different from those that would indicate the continuance of such a flow once it had begun. Also, if precipitation was already occurring, no moisture variable would be necessary since precipitation once started would be expected to continue until upslope flow ceased. Since cooperative stations do not report their observations daily, six stations of the synoptic network in and near the area were chosen for determining the occurrence of current precipitation in the region. These stations are Cheyenne, Wyo., Sidney and North Platte, Nebr., Denver and Akron, Colo., and Goodland, Kans. The definition of current precipitation for the purposes of this stratification is precipitation in any form occurring at any one of these six stations at the time of the 1230 GMT synoptic report. If precipitation is occurring the day is classified as a "P" case. It should not be confused with the precipitation day used in the verification. If no precipitation is occurring at any of the six stations the day is designated as an "NP" case.

NP CASES

The following discussion of variables and procedures applies only to "NP" cases as defined above.

One of the simplest, but very effective, variables found to indicate whether or not northeastern Colorado will have upslope or downslope conditions during the forecast period is the 1230 GMT sea level pressure at Salt Lake City. This pressure in effect indicates the presence or absence of a plateau High as well as the strength of the High if one is present. Horning [1] found a strong relationship between this variable and the occurrence of precipitation at Denver. Figure 2 shows the relationship between the sea-level pressure at Salt Lake City and the frequency of occurrence of precipitation in northeast Colorado, verified on the basis of the percent of Cooperative Stations reporting, as outlined above. The dots connected by dashed lines represent the frequency of occurrence in class intervals of 2 mb. The crosses connected by thin solid lines are values of frequency of occurrence smoothed by consecutive overlapping of 3-class intervals. The heavy solid curved line is a freehand curve fitted to the crosses.

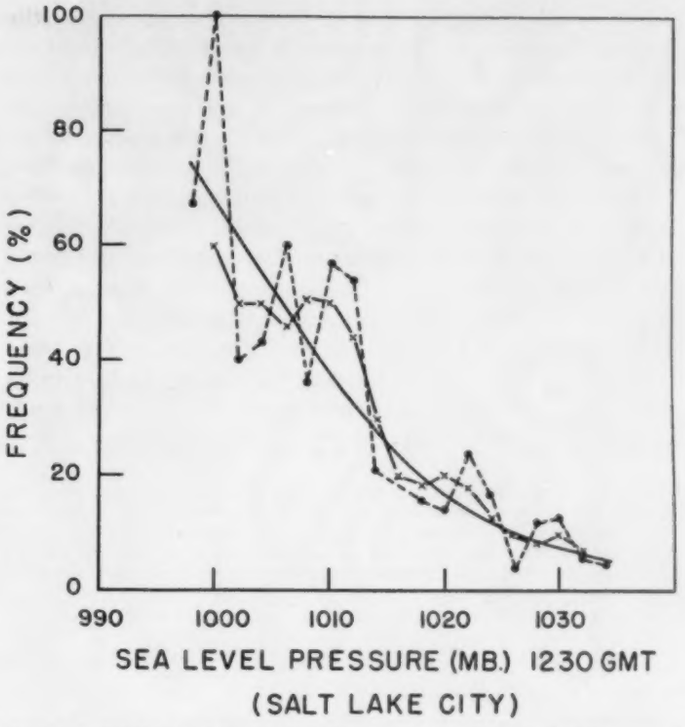


FIGURE 2.—Relationship between Salt Lake City sea level pressure and frequency of occurrence of precipitation in northeast Colorado during the forecast period. Dots connected by dashed lines represent the frequency in class intervals of 2 millibars. Crosses connected by solid lines are smoothed values by consecutive overlapping 3-class intervals. The smooth solid line is a freehand curve fitted to the crosses. (For NP cases)

Another simple, but effective, variable which gives an indication of the availability of sufficient moisture to produce precipitation in northeast Colorado is the presence or absence of precipitation in eastern Montana. This two-category variable was measured by noting the current and past 6-hour precipitation recorded on the 1230 GMT surface chart at the following six stations in or near eastern Montana: Havre, Billings, Lewistown, Miles City, and Glasgow, Mont., and Sheridan, Wyo. If current or past precipitation (including traces) was reported at any one of these stations, the variable was classified as "precipitation in eastern Montana"; otherwise, as "no precipitation in eastern Montana." Table 1 shows the relationship between this variable and subsequent precipitation in northeast Colorado, indicating

TABLE 1.—*Relationship of precipitation and no precipitation in eastern Montana to subsequent precipitation in northeast Colorado (For NP cases)*

	Total number of cases	Subsequent precipitation in northeast Colorado	
		Number of cases	Percent
No precipitation in eastern Montana	155	16	10
Precipitation in eastern Montana	109	48	44

a much higher frequency of occurrence when the variable was in the category "precipitation in eastern Montana."

The combination of the two above variables leads to a stratification such that if there is no precipitation in eastern Montana and the Salt Lake City sea level pressure is greater than 1,016 mb., the probability of precipitation occurring in northeast Colorado during the forecast period is only 3 percent. When this combination of circumstances exists, a no-precipitation forecast should be made for northeast Colorado. These results are summarized in table 2. The critical value of 1,016 mb. was arrived at by an expanded plot of the two variables. The cases falling in the quadrant labeled "B" in table 2 will be referred to as NP-B cases and those in the other three quadrants as NP-A cases.

TABLE 2.—*Joint relationship of the Salt Lake City sea level pressure and the eastern Montana precipitation variable to subsequent precipitation in northeast Colorado. The numerator of the fraction in each joint category gives the number of cases of subsequent precipitation in northeast Colorado; the denominator, the total number of cases (For NP cases)*

	Precipitation in eastern Montana	No precipitation in eastern Montana
Salt Lake City sea level pressure ≤1016 mb	$\frac{29}{59}$ 47% A	$\frac{13}{41}$ 42% A
Salt Lake City sea level pressure >1016 mb	$\frac{20}{50}$ 40% A	$\frac{3}{114}$ 3% B

Two other variables taken from past research were applied to the NP-A cases. Horning [1] developed a sea level pressure index (hereinafter referred to as the surface index) which gives an indication of whether or not upslope flow will prevail along the east slope of the mountains during the forecast period. This index is the difference between the summation of sea level pressures along the 40th parallel at points 105°, 110°, and 115° west longitude (points D, E, F in fig. 3) and the summation of pressures along the 50th parallel at the same longitudinal intersections (points A, B, C in fig. 3). The northern summation is subtracted from the southern with positive values indicating westerly or downslope flow and negative values easterly or upslope flow.

In an independent study Eberhardt [2] developed a 700-mb. index related to precipitation at Denver. If an upper-air trough of sufficient strength crosses the coast in the area of northwestern United States or British Columbia, it will continue eastward over the Rocky Mountains and will be a factor contributing to precipitation in northeast Colorado. One measure of the strength of such a trough can be obtained from a meridional index computed from the contours of the 0300 GMT 700-mb. chart. This index is computed by subtracting the sum of the 700-mb. heights at the points labeled A, B, C, and D in figure 4 from the sum of the heights at the points E, F, G, and H. A positive value of this index indicates southerly flow; a negative value, northerly flow.

These two indices of surface and upper air flow were related graphically to the occurrence of precipitation in northeast Colorado in a scatter diagram as shown in figure 5. Only NP-A cases are plotted on this chart. At the point determined by a pair of values of the indices the occurrence of subsequent precipitation was indicated by a cross, or non-occurrence, by a dot. All values of the 700-mb. index outside the range of the scale given in figure 5 were plotted on the 100 line, positive or negative as appropriate. The chart was then divided into three areas based

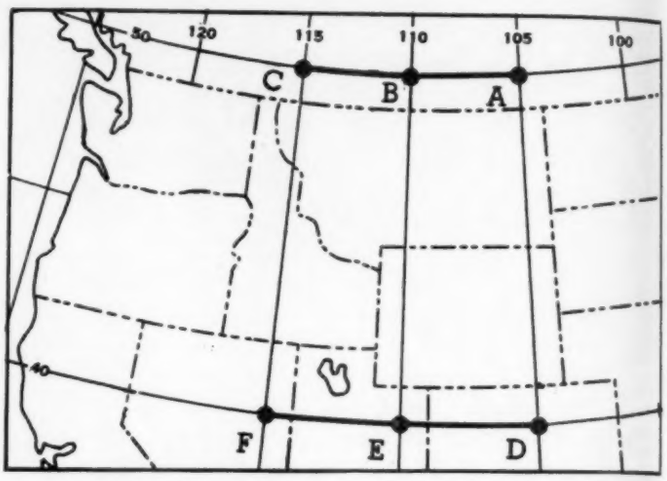


FIGURE 3.—Points used in computing surface index. Obtain 1230 GMT sea level pressure (mb.) at each point; surface index=(D+E+F)−(A+B+C).

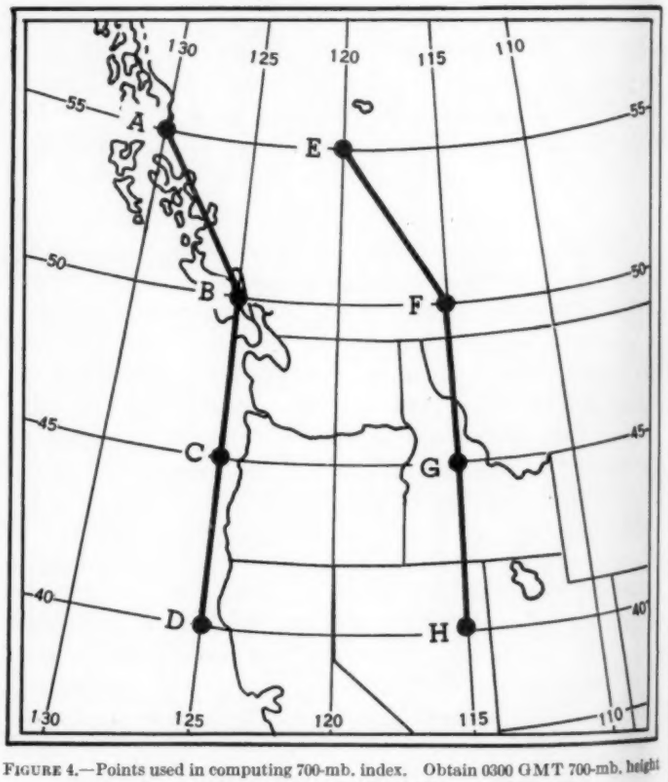


FIGURE 4.—Points used in computing 700-mb. index. Obtain 0300 GMT 700-mb. height at each point; 700-mb. index=(E+F+G+H)−(A+B+C+D).

on the percentage frequency of occurrence of precipitation as indicated. Each area was given a category number with the area of lowest percentage labeled Category I.

Extensive use is made of the 12-hour sea level pressure change chart at the Denver Forecast Center. An attempt was therefore made to incorporate the information contained in this chart (0030 GMT to 1230 GMT) into the objective procedures. It is emphasized that the one simple objective measure finally adopted from this chart by no means extracts all the information. In the authors' opinion an experienced forecaster uses the relative size, shape, intensity, and movements of the centers of rises and falls, which are extremely difficult to measure or express objectively.

The position and intensities of the centers of rises and falls were investigated in relation to the occurrence of precipitation in northeast Colorado; the position of the center of falls seemed to be most closely related. Neither the position of the center of rises nor the intensities of the centers improves materially the results obtained from the position of the center of falls alone. The position of the center of greatest falls within the area bounded by the 95th and 125th meridians and the 30th and 55th parallels of latitude was obtained. If no *center* of falls lay within the area, the position of the greatest fall within the area was taken. This distinction is important, for it is quite possible to have a separate center of falls within the area which is not necessarily the greatest fall in the area, since a large fall might exist at the edge of the area reflecting a large-fall center outside the area.

At the position thus obtained the occurrence or nonoccurrence of precipitation was plotted on a base map of the area, a cross again representing precipitation, and a dot, no precipitation. As shown in figure 6, the area was divided into five separate zones according to the frequency of occurrence of precipitation. Again, only NP-A cases were plotted on this chart.

The variables for NP-A cases were combined by a slightly modified form of the graphical correlation techniques used by Brier [5] and others [6 and 7]. Categories from figures 5 and 6 were used as coordinates of a third chart, figure 7. For each day category numbers were determined from figures 5 and 6 and the total number of cases in each combination of category numbers was tabulated. The number of precipitation occurrences was also noted. These numbers, entered in figure 7 as a fraction at the point determined by each pair of category numbers, give the frequency of occurrence of precipitation at each point. Lines were again drawn separating the data according to the frequency of occurrence. For forecasting purposes the solid line in figure 7 is the best line of separation. A forecast of precipitation is made above the line and no precipitation below the line.

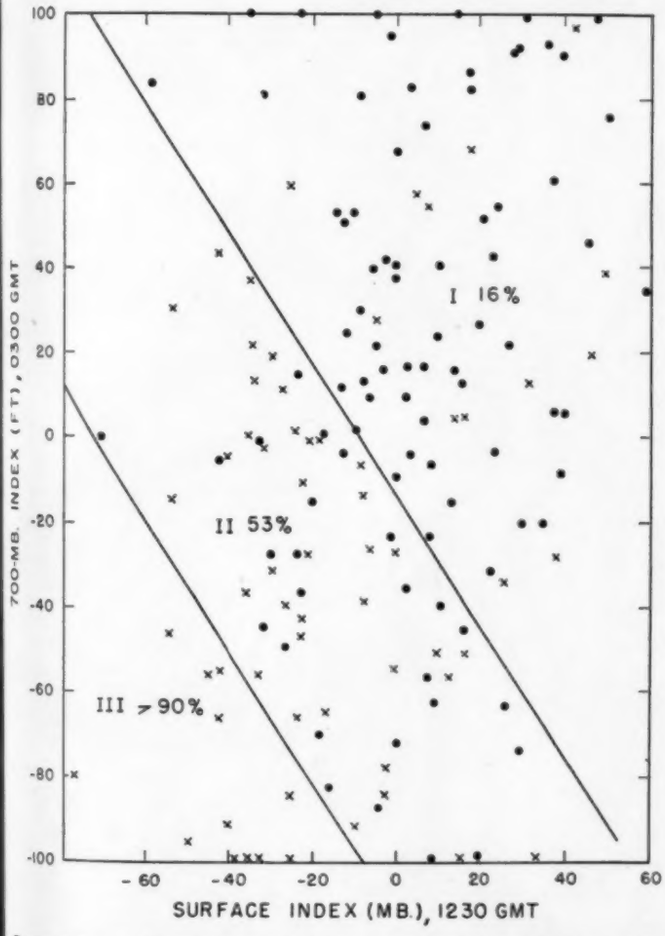


FIGURE 5.—Scatter diagram showing the joint relationship of the surface index and the 700-mb. height index with subsequent precipitation in northeast Colorado. A cross indicates precipitation and a dot no precipitation. (For NP-A cases)

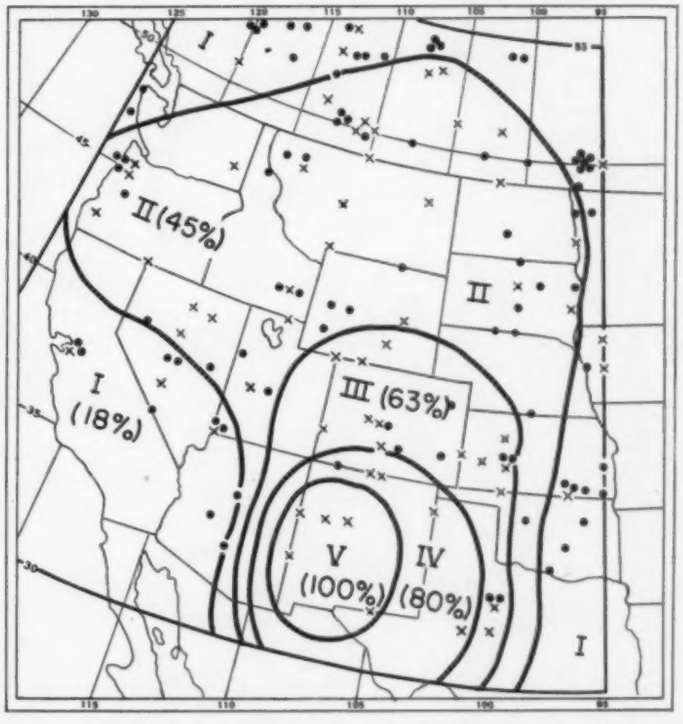


FIGURE 6.—Relationship between the position of center of 12-hour pressure falls in the area indicated and subsequent precipitation in northeast Colorado. A cross indicates precipitation and a dot no precipitation. (For NP-A cases)

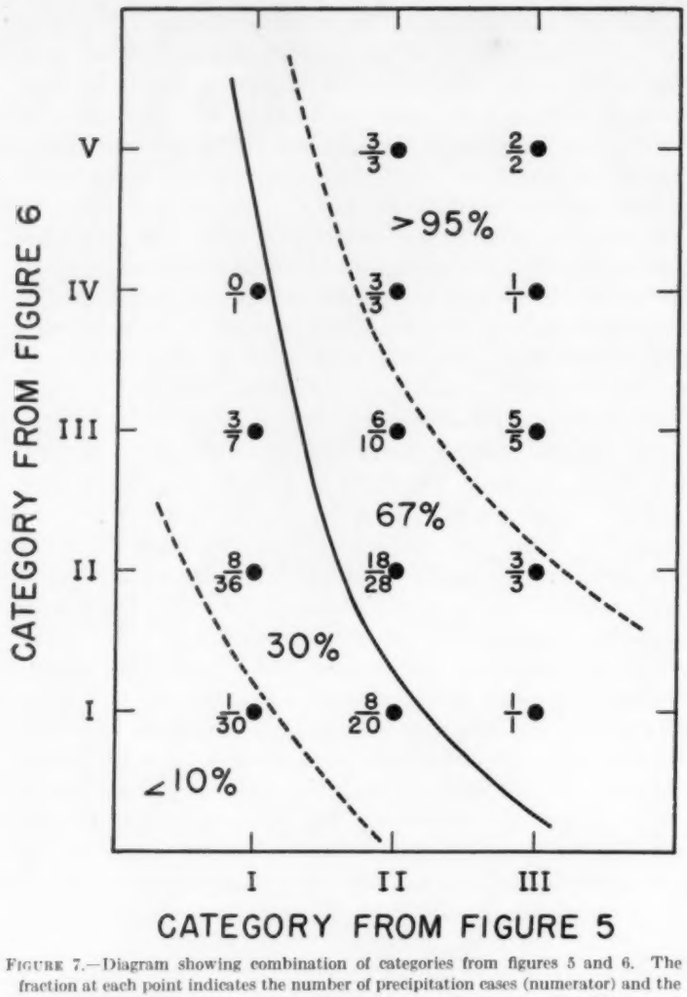


FIGURE 7.—Diagram showing combination of categories from figures 5 and 6. The fraction at each point indicates the number of precipitation cases (numerator) and the total number of cases (denominator) for the combination of categories. (For NP-A cases)

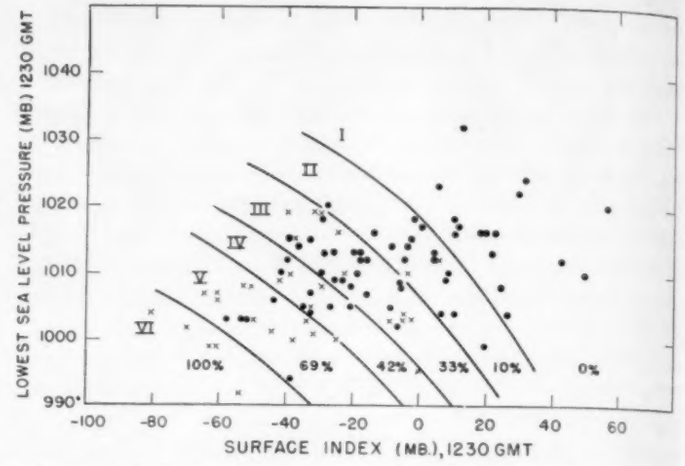


FIGURE 8.—Scatter diagram showing the joint relationship of the surface index and the lowest sea level pressure of five stations in the Southwest (Denver, Grand Junction, Salt Lake City, Grand Canyon, or Albuquerque) with subsequent precipitation in northeast Colorado. A cross indicates precipitation and a dot no precipitation. (For P cases)

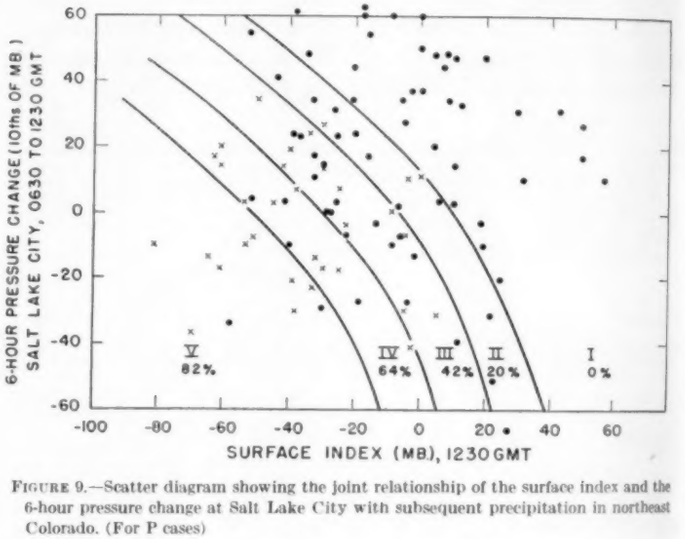


FIGURE 9.—Scatter diagram showing the joint relationship of the surface index and the 6-hour pressure change at Salt Lake City with subsequent precipitation in northeast Colorado. (For P cases)

P CASES

P cases are those in which precipitation is already falling in northeast Colorado, as indicated by the 1230 GMT reports from the six synoptic stations previously listed. The variables and procedures described below apply only to these cases.

As has been indicated, if precipitation is already occurring at 1230 GMT in northeast Colorado, the question of whether or not the precipitation will continue into the forecast period depends upon whether the pressure distribution remains such that upslope conditions will persist.

The surface index described under the NP cases (fig. 3) was again found to be strongly related to subsequent precipitation. The 700-mb. index, however, did not show a worth-while relationship in the P cases.

The intensity of the low pressure that almost always exists to the southwest of the forecast area when precipitation is currently occurring in the area was considered to be important in determining if upslope flow would continue during the forecast period. To assure objectivity in measuring the intensity of the low pressure and at the same time to cover the region in which the low pressure center normally exists, the observed 1230 GMT sea level pressure was obtained at one of five stations depending upon which station had the lowest pressure. These five stations were Salt Lake City, Utah; Grand Junction and Denver, Colo.; Grand Canyon, Ariz.; and Albuquerque, N. Mex.

Another indication of whether or not upslope conditions will persist along the eastern slopes of the Rockies is the rapidity with which high pressure is moving into or building up over the Plateau region. The 6-hour pressure change (0630 GMT to 1230 GMT) at Salt Lake City was used as a measure of this condition. A fall in pressure at Salt Lake City would indicate that the easterly flow would persist, while a rapid rise in pressure would indicate movement of the low pressure to the east, the possibility of a Plateau High building up, and subsequent downslope flow east of the mountains.

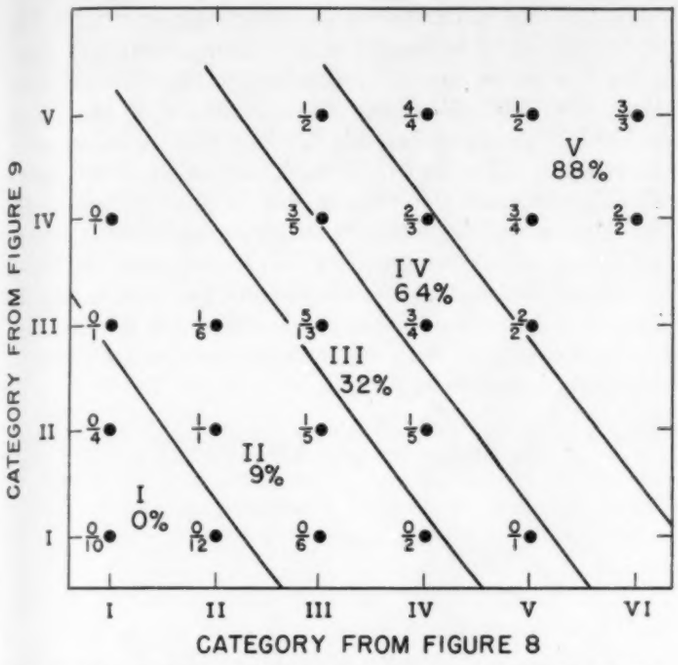


FIGURE 10.—Diagram showing combination of categories from figures 8 and 9. The fraction at each point indicates the number of precipitation cases (numerator) and the total number of cases (denominator) for the combination of categories. (For P cases)

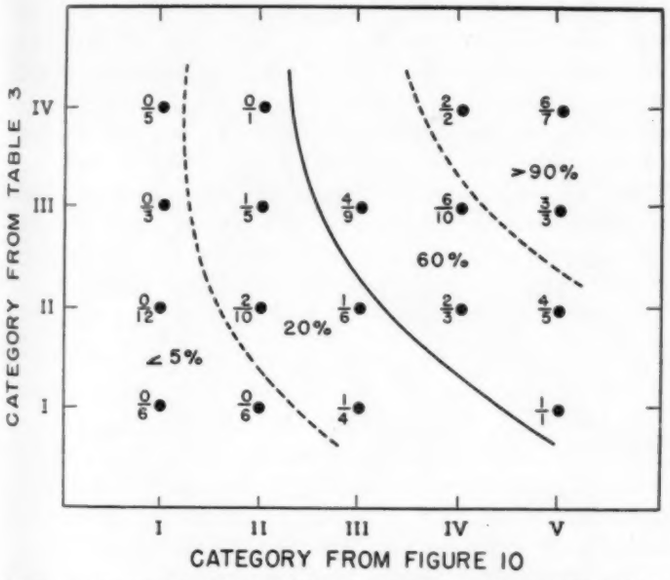


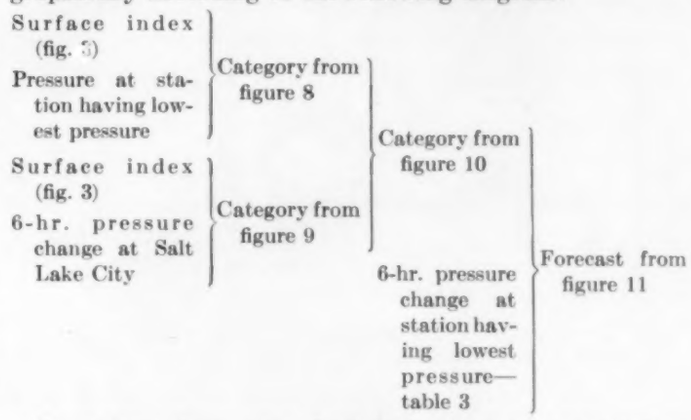
FIGURE 11.—Diagram showing combination of categories from figure 10 and table 3. The fraction at each point indicates the number of precipitation cases (numerator) and the total number of cases (denominator) for the combination of categories. (For P cases)

The change in the intensity of the low pressure to the southwest was also found to be a factor in determining whether or not upslope conditions would persist. For this purpose categories of the 6-hour pressure change (0630 GMT to 1230 GMT) at the station having the lowest pressure of the five mentioned above were utilized (table 3).

TABLE 3.—*Relationship between 6-hour pressure change at station with lowest pressure (Salt Lake City, Grand Junction, Denver, Grand Canyon, or Albuquerque) and subsequent precipitation in northeast Colorado (P cases)*

6- hour pressure change (tenths of mb.)	Total number of cases	Subsequent precipitation in northeast Colorado		Category
		Number of cases	Percent	
>+29	17	2	12	I
0 to +29	36	9	25	II
−1 to −29	30	14	47	III
<−29	15	8	53	IV

These four variables for the P cases were combined graphically according to the following diagram:


Surface index (fig. 3)
Pressure at station having lowest pressure
Category from figure 8
Surface index (fig. 3)
6-hr. pressure change at Salt Lake City
Category from figure 9
Category from figure 10
6-hr. pressure change at station having lowest pressure—table 3
Forecast from figure 11

Thus from figure 11 a final probability of precipitation for P cases is obtained. The solid line in figure 11 is the "forecasting line", a forecast of precipitation being made above the line and a forecast of no precipitation, below the line.

RESULTS

Of the 362 cases of original or dependent data 264 were classified as NP and 98 as P cases. Of the 264 NP cases 150 were stratified as NP-A and 114 as NP-B. The probability of precipitation in the NP-B cases is only 3 percent (see table 2), therefore the forecasts for all NP-B cases are for *no precipitation*, resulting in 97 percent accuracy for these cases. Of the NP-A cases 56 fall above the solid line in figure 7, 40 of which are precipitation cases, while 94 fall below the line of which 74 are no-precipitation cases. These figures give a percentage of 76 for correct forecasts for the NP-A cases.

Of the 98 P cases 40 fall above the solid line in figure 11, of which 28 are precipitation cases; 58 fall below the line, of which 53 are no-precipitation cases. This gives 83 percent correct forecasts for the P cases.

These results are summarized in table 4 which indicates the skill scores [2] and overall percent correct.

[2] Skill scores were computed from the formula: Skill score $= \frac{C-E_c}{T-E_c}$

where:

C = Number of correct forecasts

T = Total number of cases

E_c = Expected number of correct forecasts due to chance based on the marginal totals of the contingency table.

When the procedures were applied to the independent or test data the results shown in tables 5 and 6 were obtained.

TABLE 4.—*Contingency table of results of "forecasts" made by objective procedures on original data. (January, February, and March 1944, 1946, 1947, 1948)*

Observed cases		Forecasts: Precipitation	Forecasts: No precipitation	Total	
	P cases: Precipitation	28	5	33	Percent correct: 83
	P cases: No precipitation	12	53	65	Skill score: .63
	P cases: Total	40	58	98	
	NP-A cases: Precipitation	40	20	60	Percent correct: 76
	NP-A cases: No precipitation	16	74	90	Skill score: .49
	NP-A cases: Total	56	94	150	
	NP-B cases: Precipitation	0	3	3	Percent correct: 97
	NP-B cases: No precipitation	0	111	111	Skill score: .00
	NP-B cases: Total	0	114	114	
	All cases: Precipitation	68	28	96	Percent correct: 85
	All cases: No precipitation	28	238	266	Skill score: .60
	All cases: Total	96	266	362	

TABLE 5.—*Contingency table of results of "forecasts" made by objective procedures on test data (January, February, and March 1945 and 1949)*

Observed cases		Forecasts: Precipitation	Forecasts: No precipitation	Total	
	P cases: Precipitation	16	2	18	Percent correct: 78
	P cases: No precipitation	11	29	40	Skill score: .54
	P cases: Total	27	31	58	
	NP-A cases: Precipitation	16	10	26	Percent correct: 72
	NP-A cases: No precipitation	10	40	50	Skill score: .42
	NP-A cases: Total	26	50	76	
	NP-B cases: Precipitation	0	5	5	Percent correct: 89
	NP-B cases: No precipitation	0	41	41	Skill score: .00
	NP-B cases: Total	0	46	46	
	All cases: Precipitation	32	17	49	Percent correct: 79
	All cases: No precipitation	21	110	131	Skill score: .47
	All cases: Total	53	127	180	

TABLE 6.—*Contingency table of results of "forecasts" made by objective procedures on test data (November and December 1947 and 1948)*

Observed cases		Forecasts: Precipitation	Forecasts: No precipitation	Total	
	P cases: Precipitation	7	6	13	Percent correct: 74
	P cases: No precipitation	6	27	33	Skill score: .36
	P cases: Total	13	33	46	
	NP-A cases: Precipitation	16	6	22	Percent correct: 84
	NP-A cases: No precipitation	8	55	63	Skill score: .58
	NP-A cases: Total	24	61	85	
	NP-B cases: Precipitation	0	4	4	Percent correct: 92
	NP-B cases: No precipitation	0	48	48	Skill score: .00
	NP-B cases: Total	0	52	52	
	All cases: Precipitation	23	17	39	Percent correct: 84
	All cases: No precipitation	14	130	144	Skill score: .50
	All cases: Total	37	146	183	

To test the accuracy of the charts in expressing the probability of widespread precipitation in northeast Colorado, the percentage of precipitation cases for all test data was determined for class intervals of computed probability as shown in table 7. The first three observed percentages fall within their class intervals but are somewhat lower than the percentages in the original data. The percentage in the last interval, however, falls off radically from the greater-than-90-percent range indicated by the original data. Consideration of all the data indicates that instead of being greater than 90 percent, the true probability in this range based on the variables in this study is nearer 80 percent.

TABLE 7.—*Observed percentage of precipitation occurrences in class intervals of computed probability. (All test data)*

Computed probability	Total cases	Precipitation occurrences: Number of cases	Precipitation occurrences: Percent of cases
0–10	152	14	9
10–50	121	20	17
50–90	63	36	57
>90	27	18	67

Since all factors contributing to precipitation in northeast Colorado have not been evaluated, the limitations of this method should be kept in mind. Considerable skill can be obtained by the exclusive use of these techniques alone, but in certain phases it should be possible to make improvements by the subjective experience of the user. Therefore, this method should not be considered as a complete forecasting system, but as an auxiliary tool which permits the forecaster to evaluate systematically several important meteorological variables. Better results are possible if unevaluated factors are kept in mind.

SUMMARY

For purposes of application, the following summary of the method may be useful. A precipitation day is defined as a day on which more than 33⅓ percent of the selected Cooperative Stations reported precipitation during the period 1730 MST one day to 1730 MST the following day. This period coincides with the forecast period. The forecast is made from the 1230 GMT (0530 MST) surface map and 12-hour pressure change chart and the 0300 GMT (2000 MST) 700-mb. chart. The steps to be taken in making a forecast by the method are:

1. Determine if the day is a P or NP case. This is based on the current precipitation (at 1230 GMT) at the following stations: Cheyenne, Sidney, North Platte, Goodland, Akron, and Denver. If precipitation is reported at any one of these stations the day is classed as a P case. If no precipitation is reported at any of the stations the day is classed as an NP case.

2. If the day is an NP case, check the Salt Lake City sea level pressure and the past six-hour precipitation in eastern Montana at the following stations: Havre, Billings, Lewistown, Miles City, Glasgow, and Sheridan. If there has been no precipitation at any one of the six stations and the Salt Lake City pressure is greater than 1016 mb., classify the case as an NP-B case, and forecast *no precipitation*. Otherwise, classify the case as NP-A and consider other variables.
3. If the day is an NP-A case, compute the surface index and 700-mb. index as illustrated in figures 3 and 4. Enter figure 5 with the values of these two indices and determine a category number.
4. From the 12-hour pressure change chart (0030 GMT to 1230 GMT) determine the position of the center of falls within the area bounded by the 95th and 125th meridians and the 30th and 55th parallels of latitude. If no definite center lies within the area, obtain the position of the greatest fall. Enter figure 6 with this position and determine a category number.
5. Enter figure 7 with the category numbers from figures 5 and 6 and forecast *precipitation* if the point determined by the two category numbers falls above the solid line and *no precipitation* if below the solid line.
6. If the day is classified as a P case under (1) above, evaluate the following variables:
   (*a*) Surface index (fig. 3).
   (*b*) The sea level pressure at whichever of the following stations has the lowest pressure: Salt Lake City, Grand Junction, Grand Canyon, Albuquerque, or Denver.
   (*c*) The 6-hour pressure change (2330 MST to 0530 MST) at Salt Lake City.
   (*d*) The 6-hour pressure change (0630 GMT to 1230 GMT) at the station in (*b*) above having the lowest pressure.
7. Enter figure 8 with the surface index and sea level pressure at the station with lowest pressure and determine a category number.
8. Enter figure 9 with the surface index and the 6-hour pressure change at Salt Lake City and determine a category number.
9. Enter figure 10 with the category numbers from figures 8 and 9 and determine a category number.
10. Enter table 3 with the 6-hour pressure change at the station with lowest pressure and determine a category number.
11. Enter figure 11 with the category numbers from figure 10 and table 3. Forecast *precipitation* if the point falls above the solid line and *no precipitation* if below the solid line.

ACKNOWLEDGMENTS

The authors wish to acknowledge the valuable suggestions and help received from the forecast staff of the Denver Weather Bureau Office. Thanks are also extended to Miss Fay Dickerson, Research Assistant at Denver, without whose efficient help in collecting and plotting the data the work could hardly have been accomplished.

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RADAR AND SYNOPTIC ANALYSIS OF A TORNADO SITUATION

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ABSTRACT

The radar and synoptic analysis of the tornado situation of November 14, 1949, at Pierson, Fla., yields conclusions which are compatible with the author's hypothesis that the interaction zone of two intersecting pressure jump lines is a preferred region for tornado formation. Relevant to the case discussed, another mechanism for producing a pressure jump line is suggested—the "backward" moving pressure jump line.

INTRODUCTION

The pressure jump line, reflected as a sharp discontinuity on a barograph trace, has formed the basis of two earlier papers by this author. In one paper [1], it was proposed that a pressure jump line can be produced by the action of a cold front accelerating into a warm sector which contains a temperature inversion. This type of pressure jump line is related to the prefrontal squall line. In the second paper [2], it was proposed that a pressure jump line can be produced by a strong trade-wind flow coming around the southern edge of the Bermuda High and disturbed by the land mass as this flow traverses the Gulf States. A temperature inversion was required here too. In this paper, a third mechanism for the production of a pressure jump line will be proposed. All of these mechanisms follow from the analogy of pressure jumps in the atmosphere to hydraulic jumps in water and shock waves in the air as developed by Freeman [3].

In each of the two papers by this author mentioned above, it was suggested by analogy to the intersection of two unequal shock waves in gas dynamics that the intersection of two unequal pressure jump lines in the atmosphere would produce a zone of wind shear favorable for tornado formation. In [2], two cases of tornado situations verifying this hypothesis were presented.

In this paper another tornado situation will be presented and it will be shown that all available synoptic data are compatible with the above hypothesis. In addition, radar pictures taken during the period preceding and following the tornado will be presented. The precipitation echoes indicated by these radar pictures will also suggest the possibility that we are dealing with intersecting pressure jump lines. However, it should be kept in mind that these echoes are merely pictures of the portion of the precipitation area "seen" by the radar set and do not represent the pressure jump lines themselves. As suggested in [1], the precipitation pattern results from the forced lifting produced by the pressure jump line and consequently would *normally* lag the pressure jump line in both time and space.

RADAR OBSERVATIONS OF THE STORM OF NOVEMBER 14, 1949

On November 14, 1949, there developed a situation wherein a feature of the radar precipitation echo was found to be directly related to a tornado. Fortunately, continuous radar pictures were made of the storm as it moved across northern Florida. These pictures were brought to the attention of the U. S. Weather Bureau, and prints of them are reproduced in figure 1 with the kind permission of the Electronic Research Laboratory at the University of Florida.[1] On these prints are delineated the precipitation echoes picked up by the radar beam and indicated on the scope. The orientation of the echoes is with respect to north to the top, east to the right, etc. The circular rings represent distances of 20, 40, 60,... miles from the radar set.

The pictures indicate a progressive movement eastward of a long band of precipitation. Furthermore, this long radar echo appears to develop a well defined bend. At 1415 EST this bend is about 40 miles southeast of Gainesville, Fla., while at 1520 EST, the bend, which is now very pronounced, is located 60 miles east-southeast of Gainesville. It is of interest to note that the portion of the echo that is oriented NW-SE appears to extend beyond the

[1] Among the many institutions and agencies engaged in adapting radar techniques to meteorological needs is the Electronic Research Laboratory, Engineering and Industrial Experiment Station, University of Florida at Gainesville. For example, in Bulletin No. 29 [4], issued by this laboratory, there is given a completely documented discussion of the radar observation of the Florida Hurricane of August 26–27, 1949. Of singular significance to the purposes of this paper is the discussion of the authors, Latour and Bunting, relative to tornado occurrence. They observed that occasionally there developed on the spiral bands surrounding the eye of a hurricane, "wave" disturbances which were apparent for only a short time and which moved along the bands toward the center of the storm. Latour and Bunting propose that these "waves" may develop into tornadoes such as have been observed to occur within the radius of a hurricane. Such "waves," they postulate, are caused by the intrusion of colder and drier inland air into the warmer and moister air of the storm. The author of this paper concurs with the proposal that the "waves" on the hurricane bands may be related to tornado development but for a reason other than that proposed above. It has been suggested (orally by Dr. Harry Wexler, Chief, Scientific Services Division, U. S. Weather Bureau) to the author that hurricane bands might be manifestations of pressure jump lines. As such, "waves" on these bands might be the radar pictures of the cloud pattern produced by the intersection of pressure jump lines. It would follow then that "waves" on hurricane bands are but a special case of the manifestation of the intersection of pressure jump lines.

The case presented in this paper is *not* that of a tornado produced in the circulation of a hurricane, but rather represents the more general case of a wave on a radar precipitation echo and its direct relation to tornado occurrence.

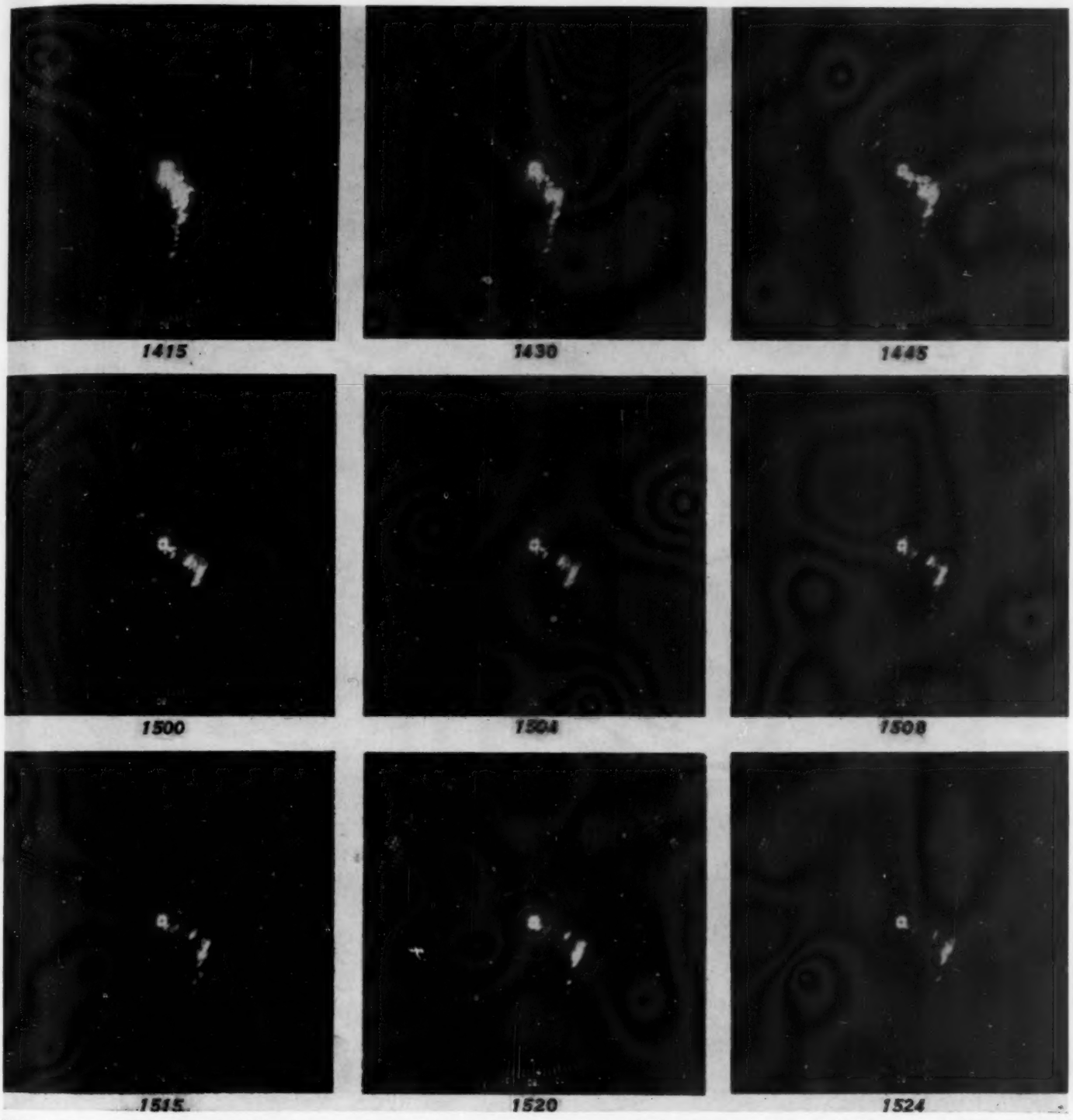

FIGURE 1.—Prints of radar pictures of the November 14, 1949, storm, taken at the Electronics Research Laboratory, Engineering and Industrial Experiment Station, University of Florida at Gainesville (reproduced here with permission of the Laboratory).

bend at 1445 EST. This might suggest an intersection of two systems in the shape of an X, but with that portion of each system lying to the east of the point of intersection being of insufficient intensity to produce precipitation echoes on the radar scope.

A tornado was reported to have struck Pierson, Fla. at 1520 EST. Pierson is located 58 miles from Gainesville and at an angle of 119°. This is in *perfect agreement* with the position of the sharp bend on the precipitation echo picture of 1520 EST.

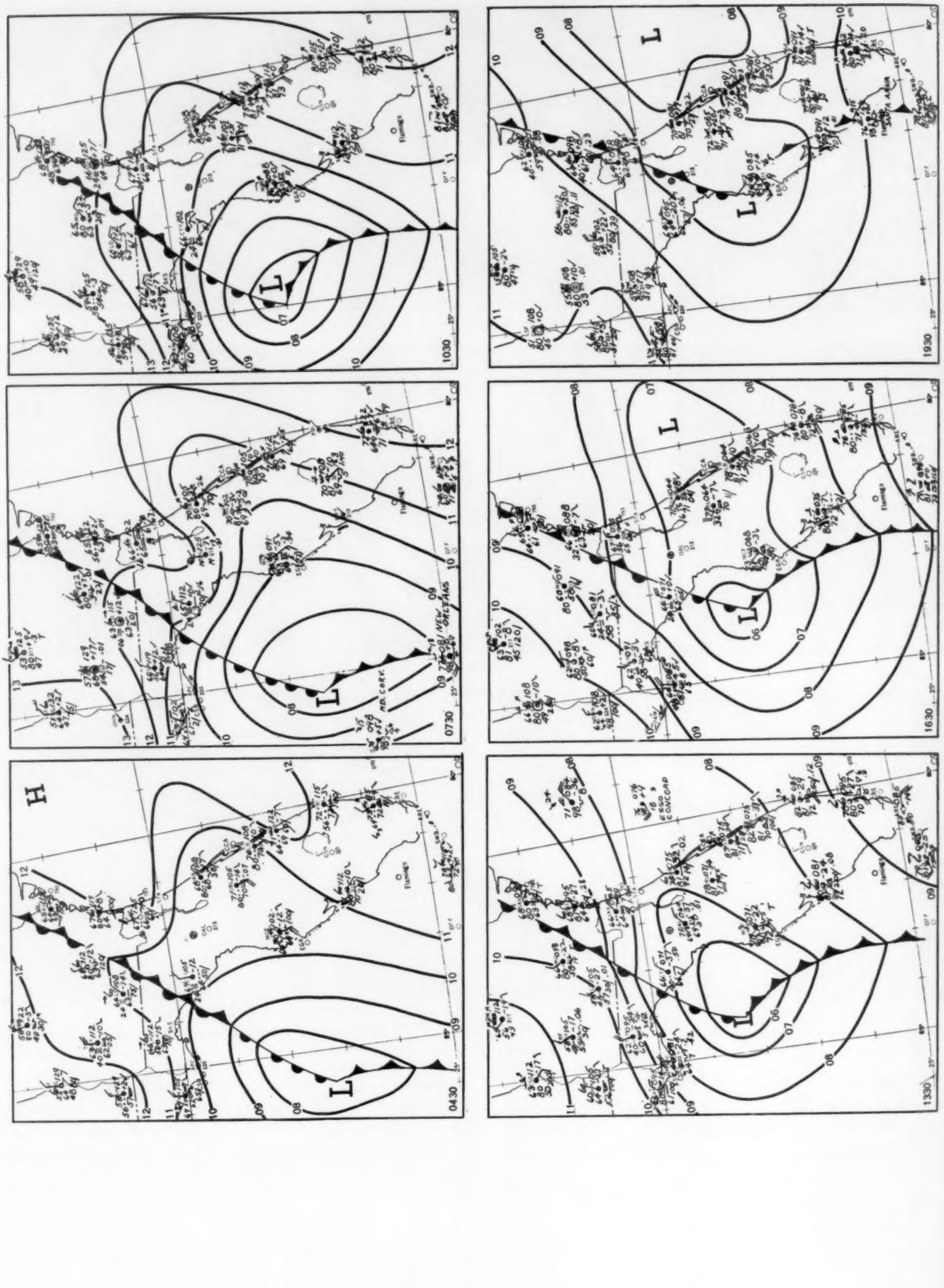

FIGURE 2.—Portion of the surface synoptic map for 3-hourly periods from 0430 to 1930 EST, November 14, 1949. ⊕ Indicates the location of Gainesville.

SYNOPTIC SITUATION

SURFACE DATA

Figure 2 shows portions of the surface synoptic maps for the southeastern corner of the United States for three-hourly periods from 0430 to 1930 EST, November 14, 1949. There are three very interesting features to be noted on these maps:

1. The front running northeastward from the wave in the Gulf of Mexico remained practically stationary throughout the period.

2. The cold front associated with this wave moved from its position in the Gulf at 0430 EST to a position roughly parallel to the western Florida coastline by 1930 EST. Unfortunately the absence of adequate data in the Gulf makes it impossible to place accurately the progressive positions of this cold front. It is not unreasonable, however, to assume that at some time after 0430 EST this front could have accelerated.

3. A trough oriented roughly NE-SW through central Florida began developing by 0730 EST, reached its maximum intensity at 1330 EST and then moved off the eastern coast of Florida as a low pressure system. It is significant for our purposes that this elongated trough produced easterlies in the northern portion of the State. The wind record at Jacksonville, Fla. given in table 1, indicates this development of easterlies after 0430 EST on the 14th.

TABLE 1.—*Surface winds at Jacksonville, Fla., November 14, 1949**

Time	Direction	Speed	Time	Direction	Speed	Time	Direction	Speed
EST		*m. p. h.*	*EST*		*m. p. h.*	*EST*		*m. p. h.*
0030	S	6	0830	E	4	1630	NE	8
0130	S	4	0930	N	6	1730	NE	10
0230	S	3	1030	E	5	1830	NE	7
0330	S	3	1130	E	6	1930	N	6
0430	S	3	1230	E	6	2030	NE	8
0530	E	4	1330	E	7	2130	NE	5
0630	E	4	1430	NE	8	2230	N	7
0730	E	3	1530	NE	7	2330	N	5

*These data were read directly from the Triple Register Recorder Sheets and as such might be considered more reliable than those wind data on the surface synoptic maps with which they may differ, since the latter are subject to errors in coding, transmission, decoding, and plotting.

Since the instrument recording these data will record only one of eight directions of the compass, it is admittedly very difficult to substantiate any claims about true wind shifts. However, in this case it appears that we are dealing with four distinct wind regimes; southerly flow until about 0430 EST, followed by easterly flow to 1330 EST, then northeasterly to 1830 EST, and finally northerly flow. The change from the first regime to the second corresponds to the development of the elongated trough in central Florida. The last change in wind regime coincides with the passage of the cold front as indicated on the 1930 EST map. The change to northeasterlies between 1330 and 1430 EST (the exact time was read as 1412 EST) corresponds to the time when the northward extension of the leading edge of the lower half of the precipitation echo would have passed Jacksonville (fig. 3). This relationship will be discussed further in a subsequent paragraph.

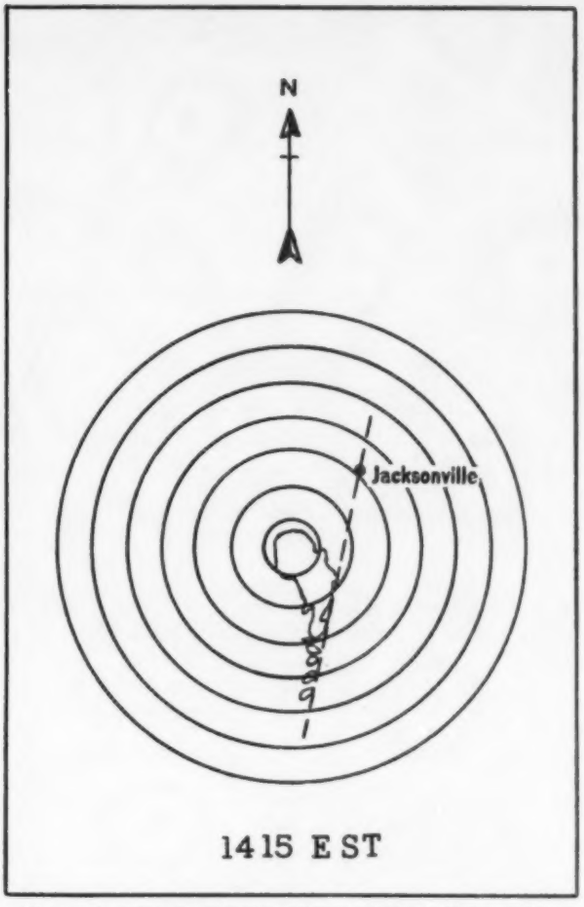

FIGURE 3.—The radar echo at 1415 EST in relation to Jacksonville.

UPPER AIR DATA

The upper air soundings at Miami and Tampa, figures 4a–b, for the morning of the 14th, each indicate a temperature inversion separating moist surface air from *relatively* drier air above. At Miami this inversion was recorded at 760–780 mb., and at Tampa the inversion is found at a lower level, at about 940–960 mb. The only available pibal at Jacksonville for the period immediately prior to the tornado (table 2) clearly indicates a low level wind shear zone corresponding to the zone of transition between the moist and drier layers. Furthermore, the type of weather reported on the surface synoptic maps for northern Florida is representative of that to be expected under stable lapse rate conditions aloft. Therefore, since all available upper air data indicate the presence of an inversion, and in the absence of any evidence to the contrary, it is reasonable to assume that the inversion extended over the entire region.

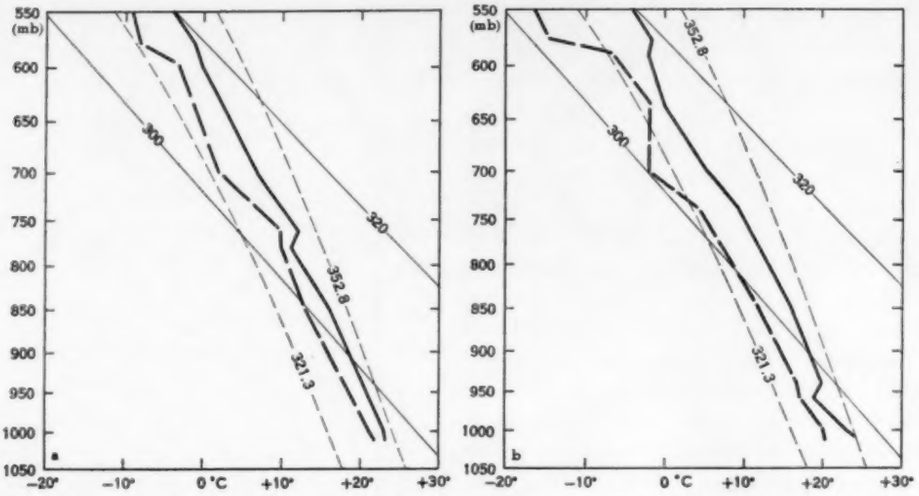

FIGURE 4.—Upper air soundings at (a) Miami, 1500 GMT and (b) Tampa, 1500 GMT, November 14, 1949. The heavy solid line is the temperature curve while the heavy dashed line is that of the dew point. The thin solid and dashed curves are adiabats and pseudo-adiabats, respectively.

TABLE 2.—*Jacksonville pibal 0300 GMT, November 14, 1949 (Wind direction (dd) to 16 points of the compass; speed (ff) in m. p. s.)*

	dd	*ff*
Surface	6	2
500 m.	8	5
1,000	14	1
1,500	13	4
2,000	11	11
2,500	11	13

RECAPITULATION OF SIGNIFICANT SYNOPTIC FEATURES

The data appear to indicate that we are dealing with the following set of conditions:

1. There is a stationary front in northern Florida oriented generally NE-SW with easterly flow directed into the front.

2. Further south there is a cold front oriented generally NW-SE which we have assumed moved quite rapidly during the morning hours of the 14th of November.

3. Throughout the northern portion of Florida there is a low level inversion.

INTERPRETATION OF THE DATA ACCORDING TO THE TORNADO HYPOTHESIS

To explain the appearance of the precipitation echoes in figure 1 and the occurrence of a tornado at the bend of the echoes we shall utilize the synoptic data described above as well as the tornado hypothesis proposed by the author [1, 2]. This hypothesis states that a preferred zone for tornado formation will result in the interaction zone of two intersecting pressure jump lines. The author has already described how a cold front, moving rapidly into a warm sector could produce a pressure jump line [1]. In our case this pressure jump line would be oriented generally NW-SE (i. e., roughly parallel to the cold front) and could have produced the upper half of the precipitation echoes. The second pressure jump line, oriented NE-SW, and associated with the lower half of the precipitation echoes could be induced by the action of the easterly current against the stationary front in northern Florida. The mechanics of the genesis of such a pressure jump line follows.

With a temperature inversion capping extensive vertical motion, air flow into the stationary front will produce an elevation of the inversion surface, which will progress as a gravitational wave away from the front (i. e., in a direction opposite to that of the flow below the inversion) as indicated in figure 5a. This picture is analogous to the flow of water in an open channel in which an obstruction has been placed (fig. 5b). In this case, a hydraulic jump will be formed and move "backward"; i. e., in a direction opposite to the flow.

Finally, the wind shift at Jacksonville at 1412 EST can now be explained as having been produced by the passage of this second pressure jump line which, in passing, imposed a northerly component on the existing easterly current.

VERIFICATION BY MEANS OF MICROBAROGRAPH DATA

An attempt was made to draw isochrone maps of pressure jump lines as reflected on the barograms, for the purpose of testing directly whether intersections of pressure jump lines were evident. The microbarograms for the 14th were reviewed for indications of pressure jumps. Unfortunately, at only about six stations did discontinuities stand out clearly enough to be considered

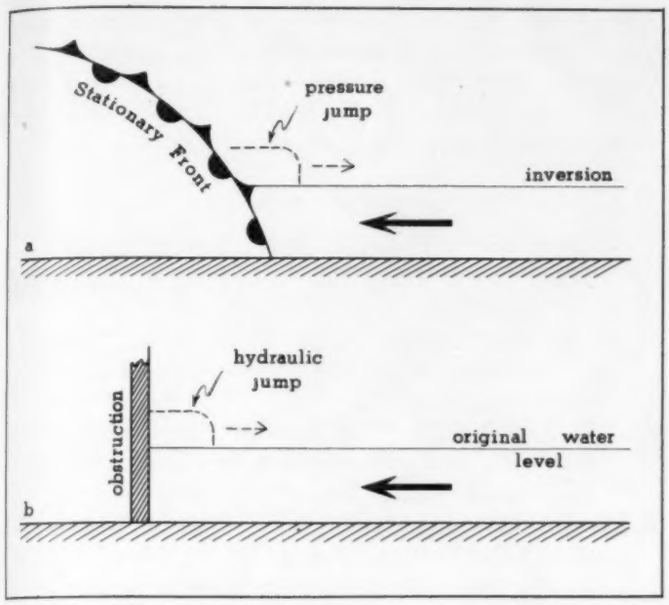

FIGURE 5.—The formation of a "backward" moving (a) pressure jump and (b) hydraulic jump.

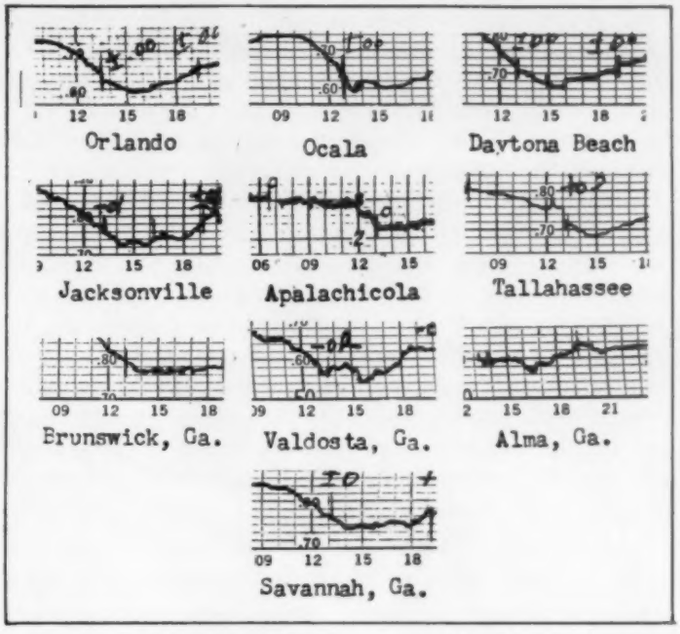

FIGURE 6.—Sections of the microbarograms used in picking off pressure jumps.

possible pressure jumps (fig. 6). Nevertheless, verification was attempted and all irregularities of the barogram for the period 1200–1800 EST that could be made to fall into a pattern of intersecting isochrones were considered. In all there were five different attempts at verification by each of five different analysts. Of these attempts, only two verified the hypothesis. The analysts whose analysis verified included the author and another analyst, both of whom had had previous knowledge of the time and place of the tornado occurrence. The author's intersection pattern, given in figure 7, represents a very good verification for both the tornado occurrence (within 20 miles of its corresponding position on the isochrone intersection line) and for the precipitation pattern represented by the radar pictures (fig. 1).

However, in general the results obtained from the attempts at verification by means of the microbarograph data are far from satisfactory since positive results were obtained by only two of the five analysts. Moreover, all of the analysts complained that the selection of pressure "jumps" was very subjective, and it must be concluded that prior knowledge by the two verifying analysts about the location and time of the tornado probably influenced their choice of barometric fluctuations to represent pressure jump lines. On the other hand it should be pointed out that only these two analysts had had any previous experience with the interpretation of barograms for pressure jumps.

CONCLUSIONS

The radar pictures of the storm of November 14, 1949 indicate that a bend on the precipitation echoes corresponds in both time and place with the tornado at Pierson,

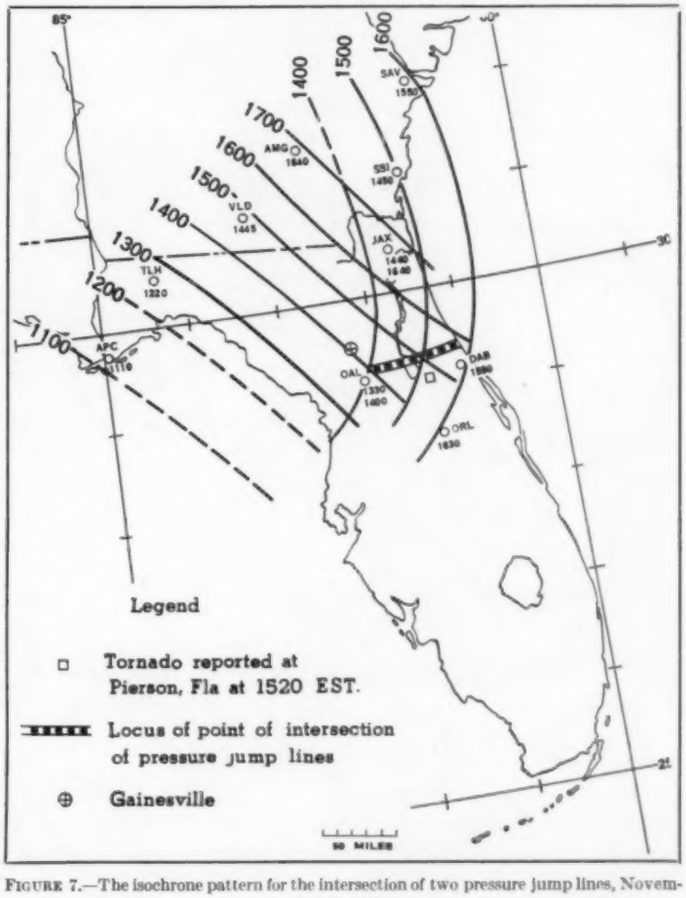

FIGURE 7.—The isochrone pattern for the intersection of two pressure jump lines, November 14, 1949.

Fla. Upon careful investigation, it was found that all available synoptic data were compatible with the conclusion that we are dealing with two intersecting pressure jump lines. These pressure jump lines are considered to have produced the pattern of precipitation echoes indicated on the radar scope. Furthermore, the occurrence of a tornado in the intersection of two pressure jump lines is in accordance with the tornado hypothesis suggested previously by the author. The failure of the microbarograph data to verify the tornado hypothesis more conclusively is attributed to three main factors: (1) the sparsity of reporting stations in the critical area, (2) the nonutilization of high speed microbarographs to separate true pressure jumps from other less sharp pressure rises, and (3) the lack of experience on the part of three of the analysts in interpreting microbarograms for pressure jumps.

ACKNOWLEDGMENTS

The author wishes to thank Mr. M. H. Latour, Electronics Research Laboratory, Engineering and Industrial Experiment Station, University of Florida for allowing him to reproduce the radar pictures and Messrs. J. E. Caskey, S. Falkowski, S. Fritz, and D. L. Harris, Scientific Services Division, U. S. Weather Bureau, for assisting with the microbarogram analysis.

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THE WEATHER AND CIRCULATION OF SEPTEMBER 1950[1]

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The upper level wave pattern of the main westerly belt in the North American region was relatively simple during September 1950, with deep troughs in the eastern Pacific and eastern Canada and a broad ridge over western Canada (fig. 1 and Charts IX to XI). In the Canadian Arctic there existed essentially one deep polar vortex with a trough extending southeastward from it into the eastern Canadian trough. Over the United States and adjacent oceans, which were south of the principal westerly stream, the circulation was more complex with troughs at 700 mb. (fig. 1) over the Great Basin, the Gulf of Mexico, and the western Atlantic and ridges over the Pacific Coast, the Great Plains, and the Bahamas. The 700-mb. height anomaly configuration in figure 1 shows an extensive area of above normal heights in Canada with a +200-ft. center in Manitoba. This area was almost completely surrounded by negative height anomalies extending from the Gulf of Alaska clockwise through the Canadian Arctic, eastern North America, and the Gulf of Mexico into the southwestern United States and Mexico. Only along the west coast of the United States did positive height anomalies extend to lower latitudes from the Canadian area. Thus the mean 700-mb.

[1] See Charts I–XI following p. 184, for analyzed climatological data for the month.

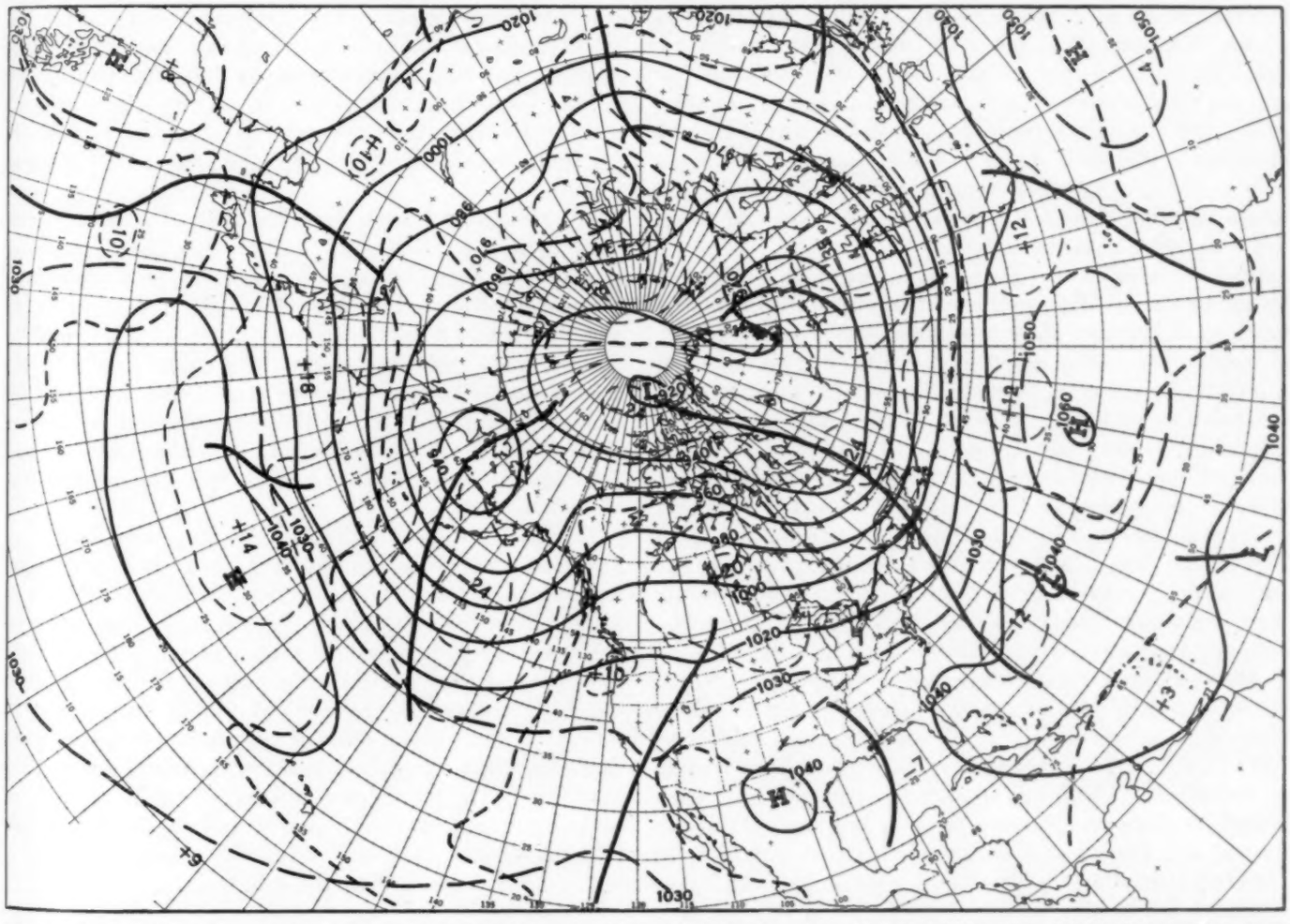

FIGURE 1.—Mean 700-mb. chart for the 30-day period August 28–September 27, 1950. Contours at 200-foot intervals are shown by solid lines, 700-mb. height departures from normal at 100-foot intervals by dashed lines with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

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gradient flow considered with respect to normal was southerly in the Gulf of Alaska and western Canada, westerly in northern Canada, northerly in eastern Canada, and easterly over practically all of the United States.

The strong northerly flow relative to normal at 700 mb. in eastern Canada led to repeated invasions of cold continental polar air into the northeastern United States, so that below normal temperatures were general in most of that area (Chart I). These cold air outbreaks were associated with anticyclonic conditions at sea level in southern Canada and the northern United States as indicated by the anticyclone paths (Chart II), and by the mean high pressure and positive pressure anomaly in the northern United States (Charts VI and II inset). Temperatures were especially low in northern New England where it was the coolest September on record at some stations in Maine. Over the central and southern United States stronger-than-normal easterly flow at sea level (Charts VI and II inset) and northeasterly flow relative to normal aloft (fig. 1) allowed the cold polar air associated with the Canadian Highs to penetrate into the Mississippi Valley, the central Plains States, and even to the eastern slopes of the Rockies. This polar air was not warmed very much as it passed through the central Mississippi Valley and the Ozarks due to the trough conditions aloft and the associated cloudiness (note center of low percentage of clear sky in that area shown in Chart IV). In fact some of the greatest negative temperature anomalies in the whole country were located in western Kansas and along the Texas-Oklahoma boundary.

Cool weather in the East was accentuated somewhat by the persistent high level smoke layers which blanketed much of the eastern third of the country in the last week of September. (See article by Smith in this issue of Monthly Weather Review.) This smoke originated in extensive forest fires in western Canada and was carried into the eastern United States by northwesterly flow aloft. (The smoke traveled with the upper circulation and was reported a few days later over Great Britain and western Europe and in early October over the Aleutians.) The smoke layers had a marked cooling effect on the surface temperatures since they restricted the incoming short wave solar radiation, but had little effect on the outgoing long wave terrestrial radiation.

Above normal temperatures were observed in North Dakota, Minnesota, and the Pacific Northwest where there were ridge conditions and above normal heights at 700 mb. (fig. 1). Temperatures were also above normal in Nevada and California despite the presence of a weak trough in the area, because 700-mb. heights were above normal and there was a well pronounced thermal low at sea level (Chart VI). The warm weather in south Texas occurred almost directly under the high center aloft even though heights were slightly below normal in this anticyclone.

Since the fastest westerlies in North America were located over the northern half of Canada during the month, most cyclone centers traveled eastward across Canada well to the north of the United States border generally along the mean 700-mb. flow (compare Chart III and fig. 1). Thus the observed precipitation pattern over the United States (Chart V and inset) was characteristic of the summer type where the distribution of precipitation is largely determined by the mean position of moist and dry tongues. This can best be demonstrated by a monthly mean isentropic chart.[2] In the absence of such a chart, however, the mean flow patterns at 700 mb. and sea level and their departures from normal can help to explain much of the September precipitation distribution.

Precipitation amounts were less than normal from the upper Great Lakes southwestward into Kansas and Oklahoma (Chart V inset). This entire region of light precipitation was located just east of the Plains ridge at 700 mb. (fig. 1) and close to the mean high center over the upper Great Lakes at sea level (Chart VI). In addition the flow relative to normal was northeasterly both at sea level and aloft (Chart II inset and fig. 1). The light precipitation in New England occurred under stronger-than-normal northwesterly flow aloft to the west of the Western Atlantic trough. Drier than normal weather also occurred in Oregon, Washington, and northern Idaho under the above normal Pacific Coast ridge at 700 mb.

The trough extending from the Gulf of Mexico northward into the Mississippi Valley was associated with greater than normal rainfall amounts in many areas from Florida northward into the Ohio Valley and eastward into the middle Atlantic States. Much of this precipitation occurred early in the month in connection with the intense hurricane which moved over Cuba and into the United States (Chart III) in the southerly flow to the east of the 700-mb. trough in figure 1. Both Jacksonville and Savannah recorded total rainfall for the month of about 17 inches.

The belt of heavy rainfall extending westward from Arkansas and Louisiana through Texas and northwestward through New Mexico and Colorado is difficult to explain from the anticyclonic northwesterly circulation on the mean 700-mb. chart in that region. Much of this rain also occurred in the early part of the month when the Gulf of Mexico—Mississippi Valley trough was an intense easterly wave, and the circulation over the South carried a large supply of moisture westward toward the Rockies. This circulation was reflected in the strong monthly mean sea level easterly and southeasterly flow (Charts VI and II inset) and in the easterly circulation with respect to normal at 700 mb. (fig. 1).

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[2] H. Wexler and J. Namias, "Monthly isentropic charts and their relation to departures of summer rainfall," *Transactions of the American Geophysical Union*, vol. 19, 1938, pp. 164–170.

The large area of abnormally heavy precipitation extending from California northeastward to Montana and North Dakota was located in and to the east of the weak 700-mb. trough in the West. The combined effects of upslope easterly flow at the surface (Chart VI) and the overrunning southwesterly flow aloft were important in producing the portion of this excessive precipitation which occurred east of the Continental Divide. Considerable snow fell in Montana and Wyoming on the last 2 days of the month in connection with a deep storm which moved through Nevada and Utah (Chart III).

In closing it is interesting to note that the basic temperature pattern over the United States during September 1950, remained substantially the same as during the two preceding months (see Chart I of July and August 1950, Monthly Weather Reviews). Much of the eastern two-thirds of the country was cooler than normal, although in central sections there was some moderation of the extreme negative temperature anomalies of the two previous months. Precipitation was still copious in many sections of the country in September, but the heavy rains in Kansas and Oklahoma in July and August did not continue into September.

THE WIDESPREAD SMOKE LAYER FROM CANADIAN FOREST FIRES DURING LATE SEPTEMBER 1950

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INTRODUCTION

During the latter part of September 1950, an extensive layer of smoke originated from forest fires in the Canadian Provinces of British Columbia and Alberta. Subsequently it spread over large areas of Canada and the eastern United States. The resulting unusual appearance of the sky and sun and the diminution of normal daylight caused widespread interest among meteorologists and the public alike. This report describes some of the information about this phenomenon which has been collected and analyzed during the first three weeks in October.

THE SOURCE AND SPREAD OF THE SMOKE

The weather in British Columbia and Alberta was unseasonably warm and dry during the first half of September, contributing materially to the onset of extensive forest fires. According to conservative estimates furnished by the Canadian Embassy at Washington, D. C., approximately 60 fires burned in British Columbia, and 37 were counted by forestry officials in Alberta. The fires, beginning about mid-September, extended west from Grande Prairie, Alberta, through Fort St. John, British Columbia, to the foothills of the Rockies and north to Fort Nelson, British Columbia, with others raging near Wanham, Alberta, 340 miles northwest of Edmonton, Alberta, and Newbrook, Alberta, 70 miles north of Edmonton. The dashed hatching in figure 1 indicates the principal fire area. Undoubtedly other scattered forest or tundra fires in western Canada contributed smoke to the atmosphere since the fall season is usually fraught with such fires. During the last week of September, light snow and rain helped extinguish most of the fires.

The smoke from the fires spread eastward passing over central Canada, then southward over the Great Lakes region and the eastern United States as far south as Georgia and Tennessee. The denseness and unusual optical effects of the smoke first became very noticeable over the northeastern United States on September 24. The weather observer at Idlewild, N. Y., reported that the sun appeared pink; at Allentown, Pa., and Buffalo, N. Y., it looked purple; at Findlay, Ohio, and Parkersburg, W. Va., blue; and at Washington, D. C., lavender. The sky was usually described as yellowish or greyish-tan. Williamsport, Pa.; Dunkirk, N. Y.; Martinsburg, W. Va.; Sault Ste. Marie, Mich.; and Nakina, Ontario, were some of the stations reporting unusually dark conditions during the day with a few experiencing reduction of light to nighttime darkness. By noon September 26, the smoke had been carried across the Atlantic as indicated by the observation of a blue sun from the Isle of Man in the British Isles. Later other reports of unusual optical effects came from European stations.

The smoke aloft persisted over the northeastern United States at least until the afternoon of September 29 when generally cloudy conditions prevented further observations of it from the surface. It was certainly absent from the Washington area by 1630 EST September 30 when clear skies were again reported.

Such widespread smoke from forest fires has been observed in past years. In 1918 forest fires in Minnesota produced smoke which was observed as far away as Texas and South Carolina [1]. The record of dark days in the United States resulting from smoke pollution extends back to 1706 according to Plummer [2]. The effects of smoke pollution have also been observed for centuries as dry fogs and colored rains. Forest fires are the chief cause of widespread smoke aloft, but many notable ex-

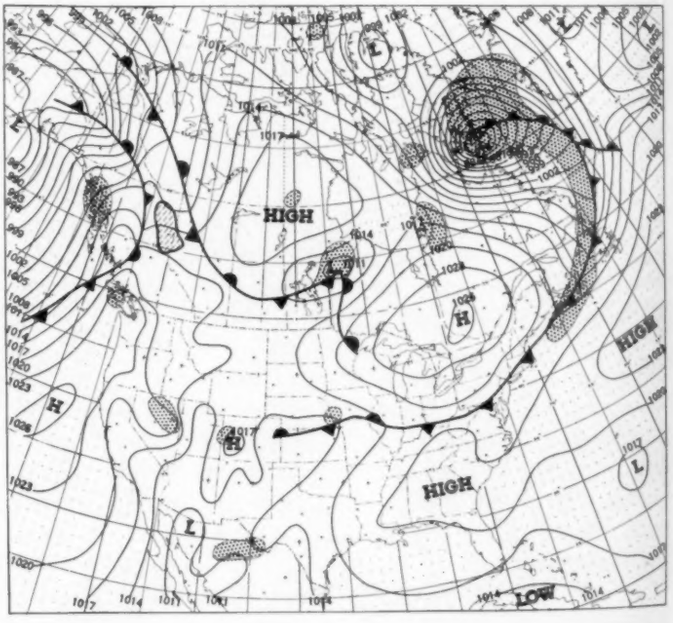

FIGURE 1.—Surface weather map for 0030 GMT, September 20, 1950. Shading indicates areas of active precipitation. Dashed hatching indicates principal area of forest fires.

amples of smoke and dust from volcanic eruptions are recorded as well [3]. The eruption of Krakatoa in 1883 is well known as the cause of very extensive smoke and dust aloft as well as of brilliant optical effects [4].

THE SYNOPTIC SITUATION IN THE FIRE AREA

During the period September 5 to 23, that part of British Columbia and Alberta shown in figure 1 as the fire area experienced a drought principally due to a ridge of high pressure at the surface and aloft which occupied the region most of that period. The ridge acted as an efficient blocking obstacle to the passage of the customary train of maritime fronts. The fronts that moved up to the ridge weakened markedly or frontolized; consequently almost no precipitation occurred in the region. Figure 1 illustrates one such weak maritime Pacific front that passed through the area. The region between the maritime occlusion and the stationary polar front experienced temperatures in the mid-seventies. Some rain fell west of the Rockies, but the east side remained dry due to the combined effect of topography and the semi-permanent ridge which weakened the front as it approached. These conditions are representative of the drought period preceding the forest fires.

As would be expected in a persistent ridge, the surface winds were generally light and variable. These factors contributed not only to the production of the forest fires, but also to the accumulation of a large amount of smoke in the fire area. An examination of the surface observations in the area for September 17–24 clearly shows the large, dense supply of smoke available for transport by the winds to other regions. The observations of September 22, 23, and 24, the period of maximum fire activity, contain evidence of the smoke in the form of reduced visibility (less than 1 mile at many stations), obscured skies, remarks of smoke aloft, or pilot reports of smoke and forest fires in the vicinity.

UPPER AIR CONDITIONS SEPTEMBER 22–27, 1950

Since the smoke produced at the surface in British Columbia and Alberta was observed several days later as a thick layer aloft far to the east it was obviously necessary to examine the upper air conditions to establish a sequence of events in the movement of the smoke. The 700-mb. charts of 0300 GMT September 22, 24, and 27 were selected to illustrate the upper air flow (figs. 2, 3, and 4). The pattern of flow at 500 mb. was similar to that at 700 mb.

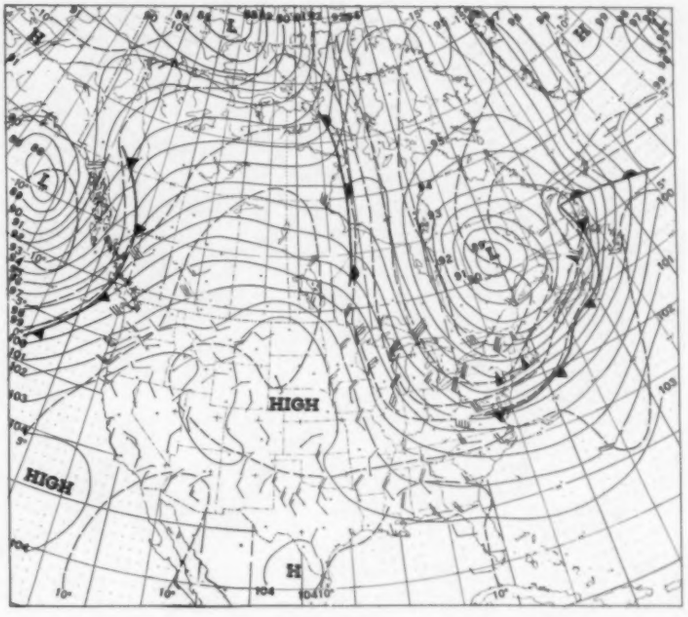

FIGURE 3.—700-mb. chart for 0300 GMT, September 24, 1950.

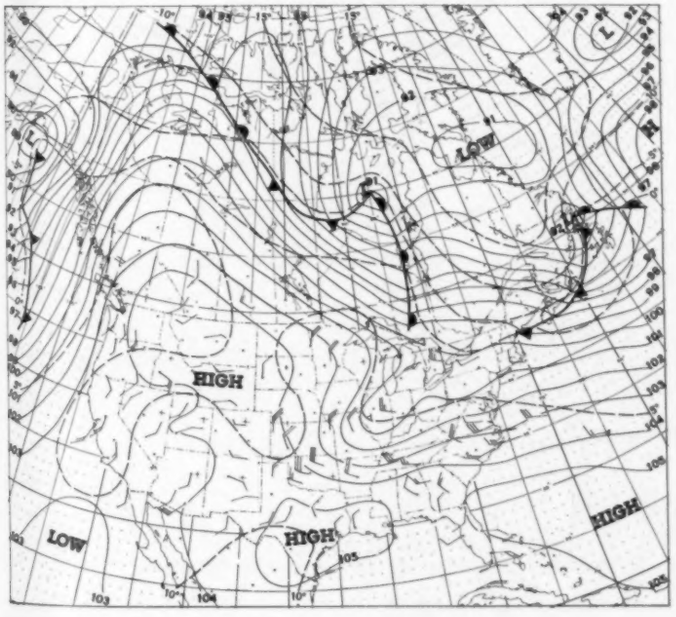

FIGURE 2.—700-mb. chart for 0300 GMT, September 22, 1950. Contours (solid lines) at 100-foot intervals are labeled in hundreds of feet. Isotherms (dashed lines) are in intervals of 5° C. Barbs on wind shafts are for wind speeds in knots; full barb = 10 knots, half barb = 5 knots, and pennant = 50 knots.

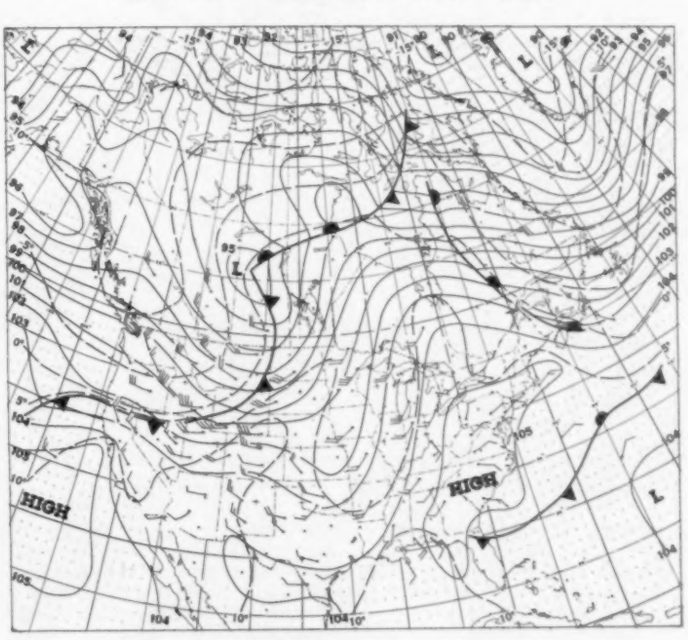

FIGURE 4.—700-mb. chart for 0300 GMT, September 27, 1950.

The period September 22 through 24 was characterized by a ridge over the western United States and Canada and a Low in eastern Canada with a well defined northwesterly or northerly current over central Canada and the eastern United States. Figures 2 and 3 are sufficient to give the general impression that smoke added to the atmosphere over the fire area was swept over central Canada and southward over eastern United States. An attempt was made to demonstrate this by calculating trajectories both up and down stream on the 700-mb. and 500-mb. surfaces. It was found that such trajectories did not correspond to the observed location of the smoke layer or to the proper time sequences. In order to track the smoke more precisely the following procedure was used.

All available reports of the height of the base and top of the smoke layer were studied. These consisted mainly of pilot reports over the eastern United States. It was found, as might be expected, that the smoke layer was not observed at the same height from place to place and time to time. Also multiple layers were reported by pilots. On September 24 the base was reported variously 12,000 to 14,000 feet over Pennsylvania, and a pilot reported that he was in dense smoke at 17,000 feet over Sault Ste. Marie. On September 25, the base was reported variously 11,000 to 14,000 feet and the top 14,500 feet to indefinitely higher. By September 26, the base was 9,000 to 11,000 feet and top around 14,500 feet. Then by September 27 and 28, the base was 6,000 to

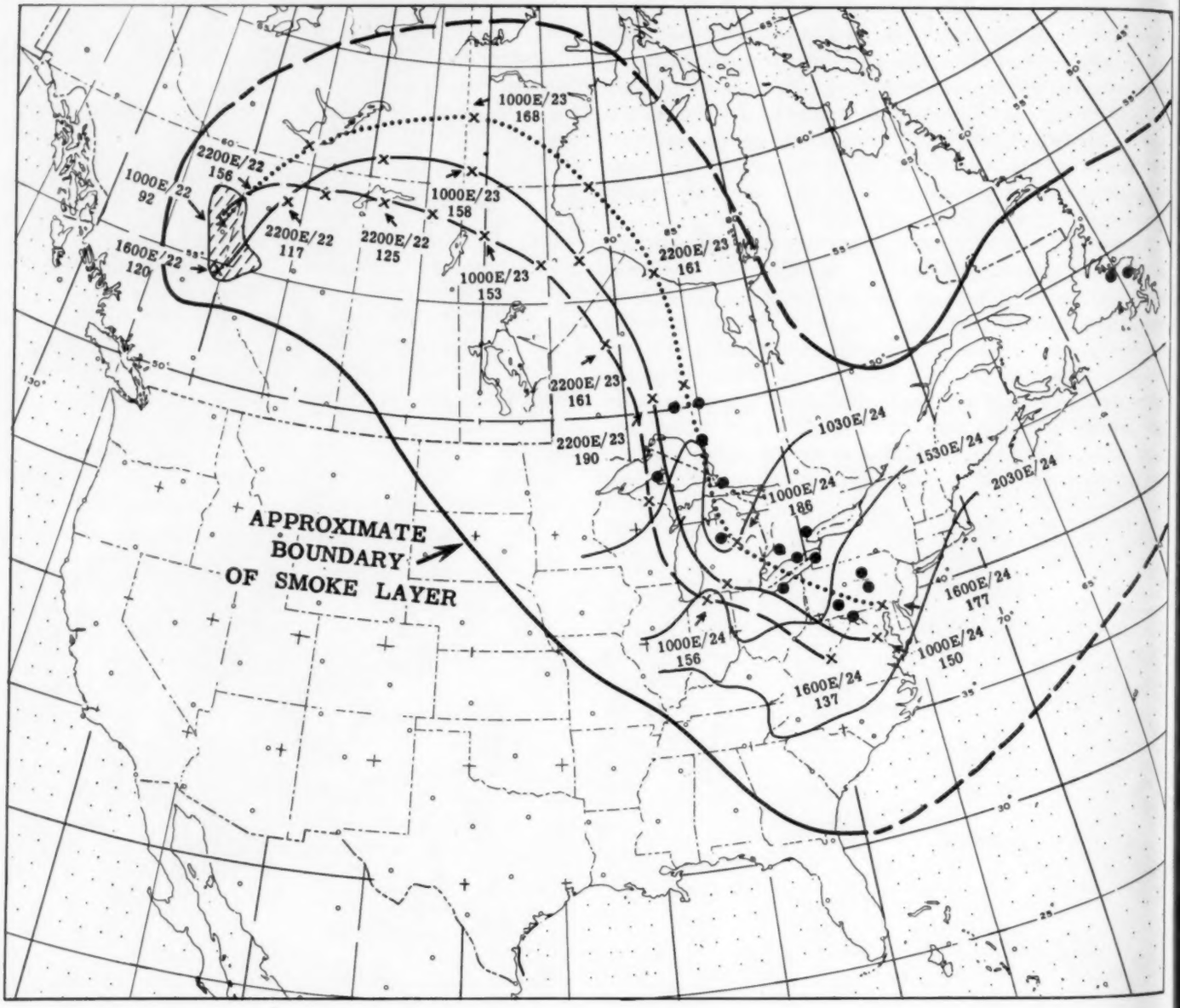

FIGURE 5.—Trajectories of air parcels calculated on isentropic charts of θ=312° A. Dashed hatching indicates fire area. Three-digit numbers by trajectory points are heights in hundreds of feet. Large dots near Great Lakes mark stations reporting greatly diminished daylight on September 24. Large dots in Newfoundland mark the same condition on September 25. Dashed parts of smoke boundary are problematical. Thin solid lines across the Great Lakes and eastern United States are isochrones at 5-hour intervals on September 24 showing southeastward progress of the smoke layer.

9,000 feet and top 10,000 to 15,000 feet. The appropriate adiabatic diagrams were examined in order to coordinate the reported heights with significant lapse rate changes. It was found that the reported heights did not correspond to a constant pressure surface; however, the potential temperature of 312° A was common to a majority of the heights. This suggested that a series of isentropic charts of potential temperature 312° would be superior to constant pressure charts for reconstructing trajectories of air parcels from the fire area. A series of 7 such isentropic charts spaced at 12-hour intervals was prepared for the period 0300 GMT September 22 through 0300 GMT September 25 and trajectories were calculated in 6-hour steps using the isentropic stream functions and a set of geostrophic wind scales designed to give velocities in knots. Sample trajectories calculated on these charts are shown in figure 5.

The examination of the adiabatic charts revealed the atmosphere over western Canada to be conditionally unstable to 6,000 feet and at times as high as 18,000 feet. The convection caused by the heat from the fires carried the smoke several thousand feet aloft initially, and the instability of the air assisted farther rise to heights corresponding to those of the 312° potential temperature surface. In figure 5 the heights (accurate to ±300 feet) along the trajectory on the 312° surface are shown to vary between 9,200 and 15,600 feet in the fire area.

The trajectories beginning 1000 EST September 22 (dashed) and 2200 EST September 22 (dotted) in the fire area show the approximate path of the main stream of smoke. Note how the dotted trajectory runs through the middle of the group of marked stations near the Great Lakes. The marked stations are some that reported very dark sky conditions or reduction of light to nighttime conditions on September 24 indicating a thick, dense, smoke layer aloft. The marked stations in Newfoundland experienced the same condition on September 25.

Trajectories were also calculated upstream from points in the northeastern United States. One is shown in figure 5 (solid line). It also corresponds well with the main stream of smoke. In the calculations of trajectories it was found the resulting particle path is very sensitive to the choice of the starting place and time. By varying each initial condition it can be shown that air passing over the fire area moved over approximately the area designated in figure 5 as that covered by the smoke.

The three isochrones in figure 5 were drawn after summarizing the hourly surface reports. They agree reasonably well with the times on the trajectory points and illustrate the southward progress of the smoke.

While the smoke proceeded eastward, a polar outbreak developed in the Hudson Bay region as a cyclone on the polar front deepened over Hudson Bay. The low contour center aloft associated with the surface cyclone deepened rapidly forming a strong northerly current just west of Hudson Bay as illustrated by figures 2 and 3. The smoke layer was caught up by this rapid current above the cold dome and accelerated to speeds greater than 50 knots. If this development had not occurred it is improbable that the smoke layer would have covered such large areas of the United States.

The cold dome of continental polar air that moved southward over the northeastern United States on September 23 and 24 extended to approximately 14,000 feet. Comparing this height with the height of the smoke layer as reported by pilots it is established that the smoke layer was in the maritime Pacific air above the polar dome. The Pittsburgh sounding reproduced in figure 6 shows the top of the continental polar air near 600 mb. (approximately 14,000 feet) with a potential temperature of approximately 310° A. The Washington sounding of 3 days later, also illustrated in figure 6, shows the continental polar dome had subsided to 740 mb. (approximately 8,500 feet) with a potential temperature of approximately 308° A. This height corresponds well with the reported height of the smoke layer on September 27.

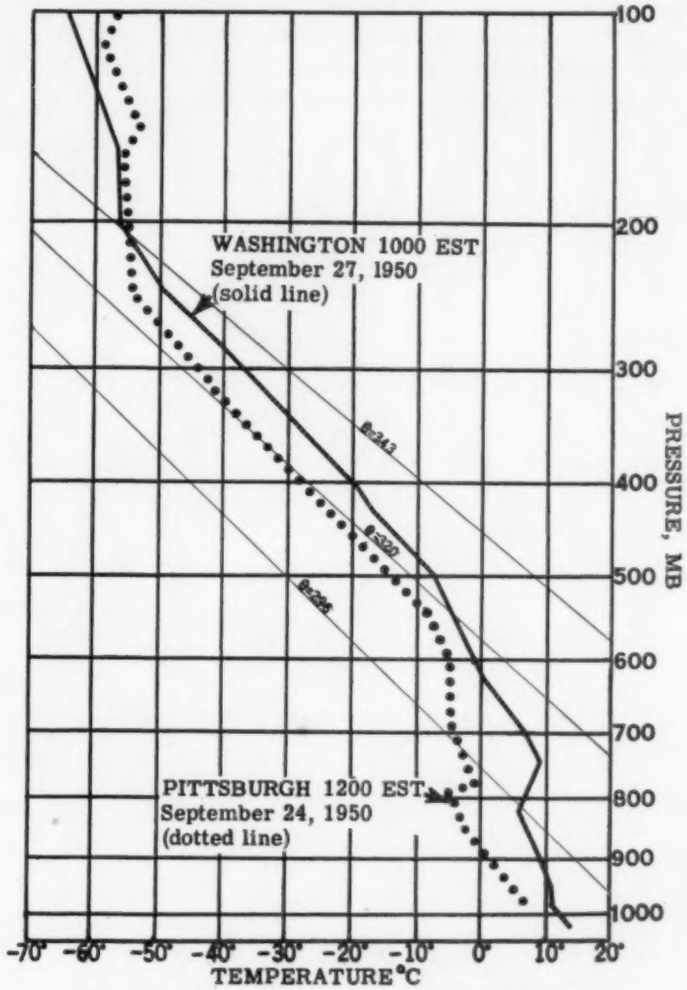

FIGURE 6.—Radiosonde observations plotted on a pseudo-adiabatic diagram: Pittsburgh, Pa., 1200 EST, September 24, 1950; Washington, D. C., 1000 EST, September 27, 1950.

One of the interesting aspects of the smoke layer was its persistence over the northeastern United States during most of the week beginning September 24. An examination of the upper air situation revealed one explanation for the persistance. On September 24 and 25, a ridge located to the west of this area contributed to the production of the northwesterly current over the area as shown in figures 2 and 3. This current provided a continuous supply of smoke on those days. By September 26, the ridge had moved over the area producing a large region of light, variable winds aloft. Figure 4 illustrates this condition. Apparently a large quantity of the smoke was cut off from the main stream of the westerlies and remained trapped over the northeastern United States.

EFFECTS OF THE SMOKE LAYER

The smoke layer reduced the amount of solar radiation received at the ground, and consequently the temperatures recorded by stations in the smoky area were affected. Mr. Sigmund Fritz of the U. S. Weather Bureau, investigating the effect on the temperature at Washington on September 26 and 27, has made preliminary estimates that the maximum temperature was lower than it otherwise would have been by about 10° F., and the minimum temperature higher by a smaller amount.

This paper has dealt with the synoptic aspects of the smoke layer. Additional information about the insolational and optical aspects can be found in a paper by Dr. H. Wexler published in *Weatherwise* [5].

ACKNOWLEDGMENTS

The author acknowledges the valuable assistance of Mr. D. Lee Harris in calculating isentropic stream functions and Mr. Kenneth M. Nagler in calculating trajectories.

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5. H. Wexler, "The Great Smoke Pall of September 24–30, 1950," *Weatherwise*, vol. 3, No. 6, December 1950.

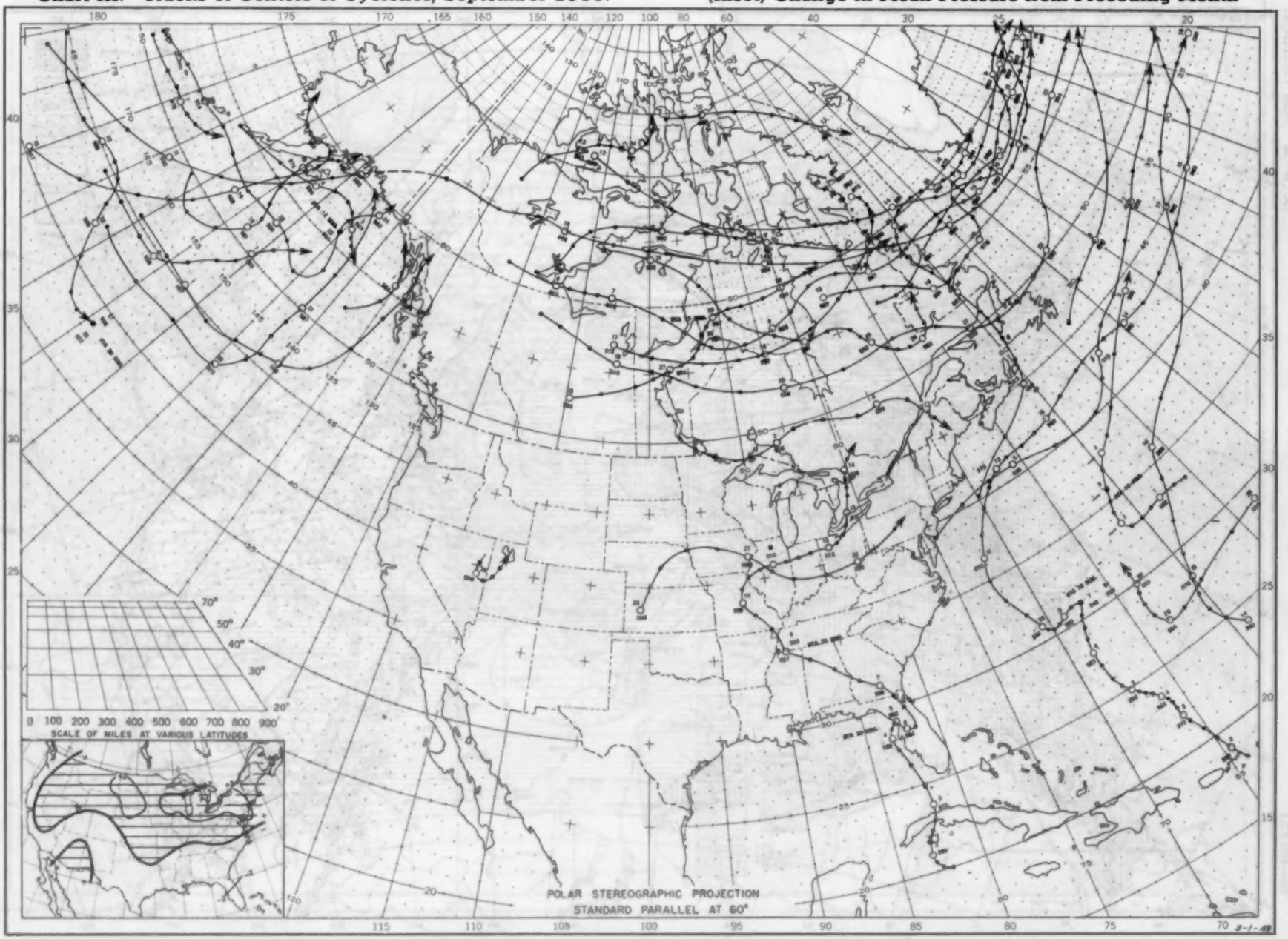
Chart I. Departure (°F.) of the Mean Temperature from the Normal, and Wind Roses for Selected Stations, September 1950

Chart II. Tracks of Centers of Anticyclones, September 1950. (Inset) Departure of Monthly Mean Pressure from Normal

0 100 200 300 400 500 600 700 800 900
SCALE OF MILES AT VARIOUS LATITUDES
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

Circle indicates position of anticyclone at 7:30 a. m. (75th meridian time). Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart III. Tracks of Centers of Cyclones, September 1950. (Inset) Change in Mean Pressure from Preceding Month



Circle indicates position of cyclone at 7:30 a. m. (75th meridian time) Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart IV. Percentage of Clear Sky Between Sunrise and Sunset, September 1950

Scale of Shades
Over 70 percent
60 to 70 percent
50 to 60 percent
40 to 50 percent
Under 40 percent
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Chart V. Total Precipitation, Inches, September 1950. (Inset) Departure of Precipitation from Normal

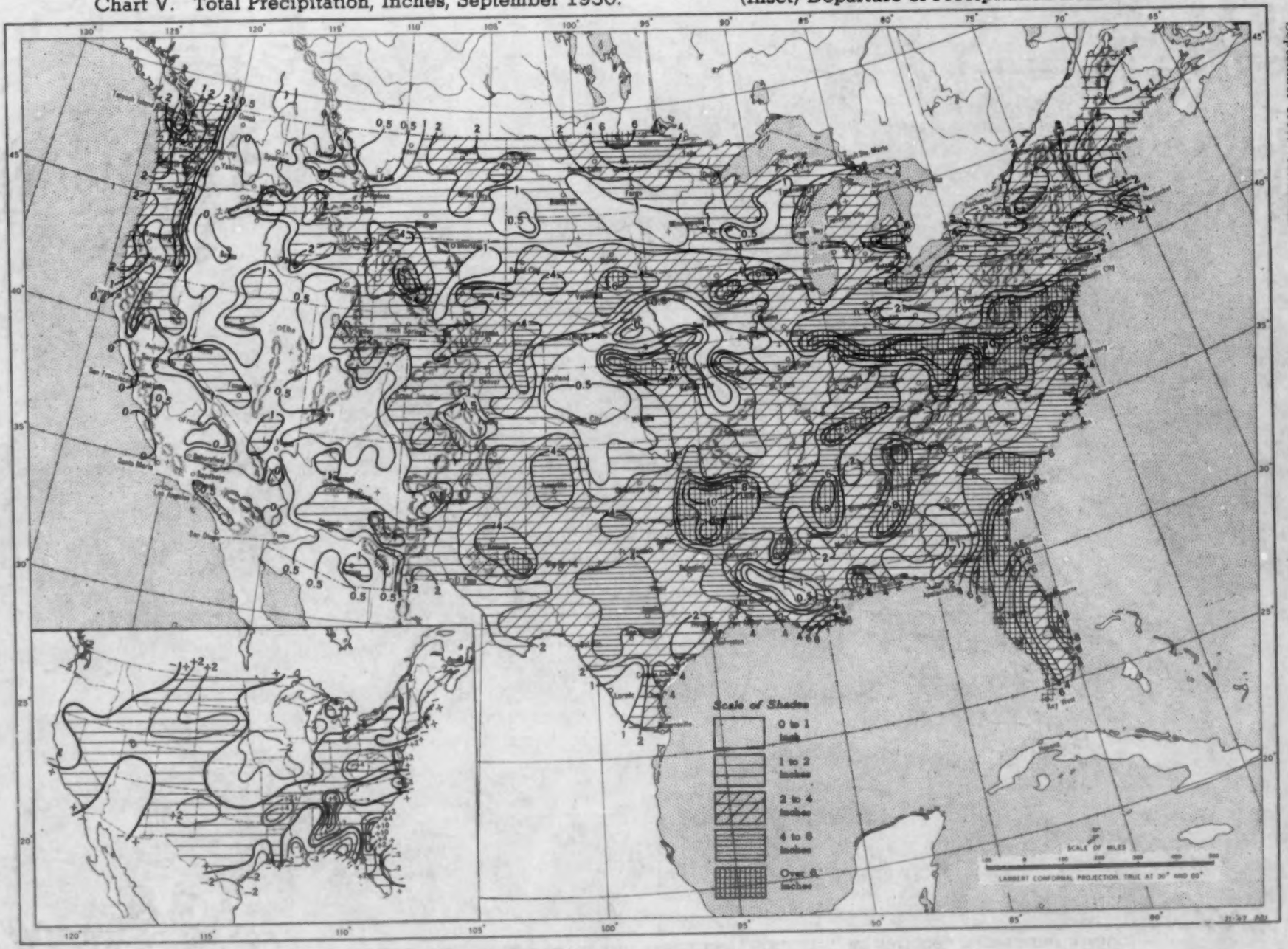

Scale of Shades
0 to 1 Inch
1 to 2 Inches
2 to 4 Inches
4 to 6 Inches
Over 6 Inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Chart VI. Mean Isobars (mb.) at Sea Level and Mean Isotherms (°F.) at Surface., September 1950

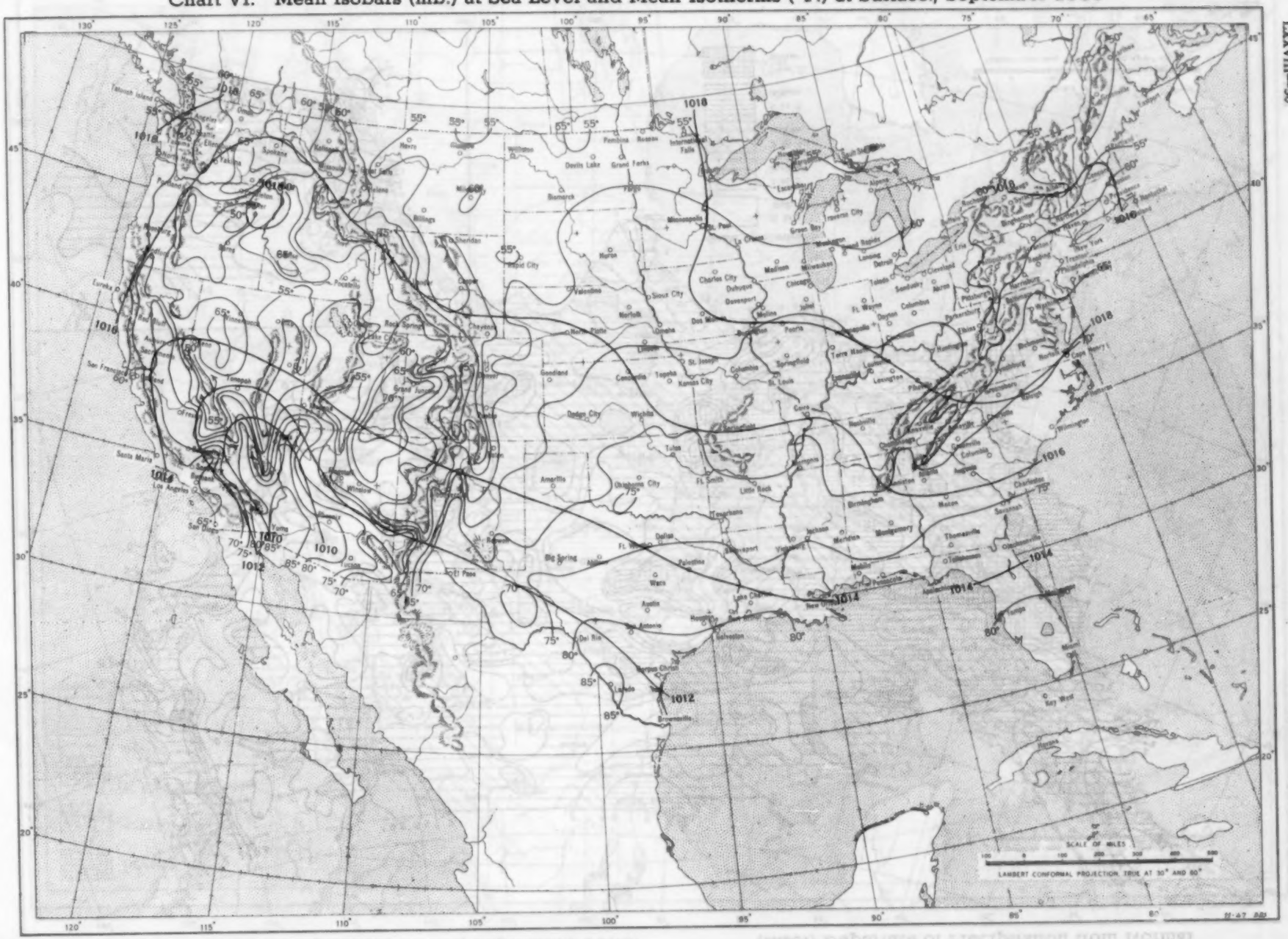
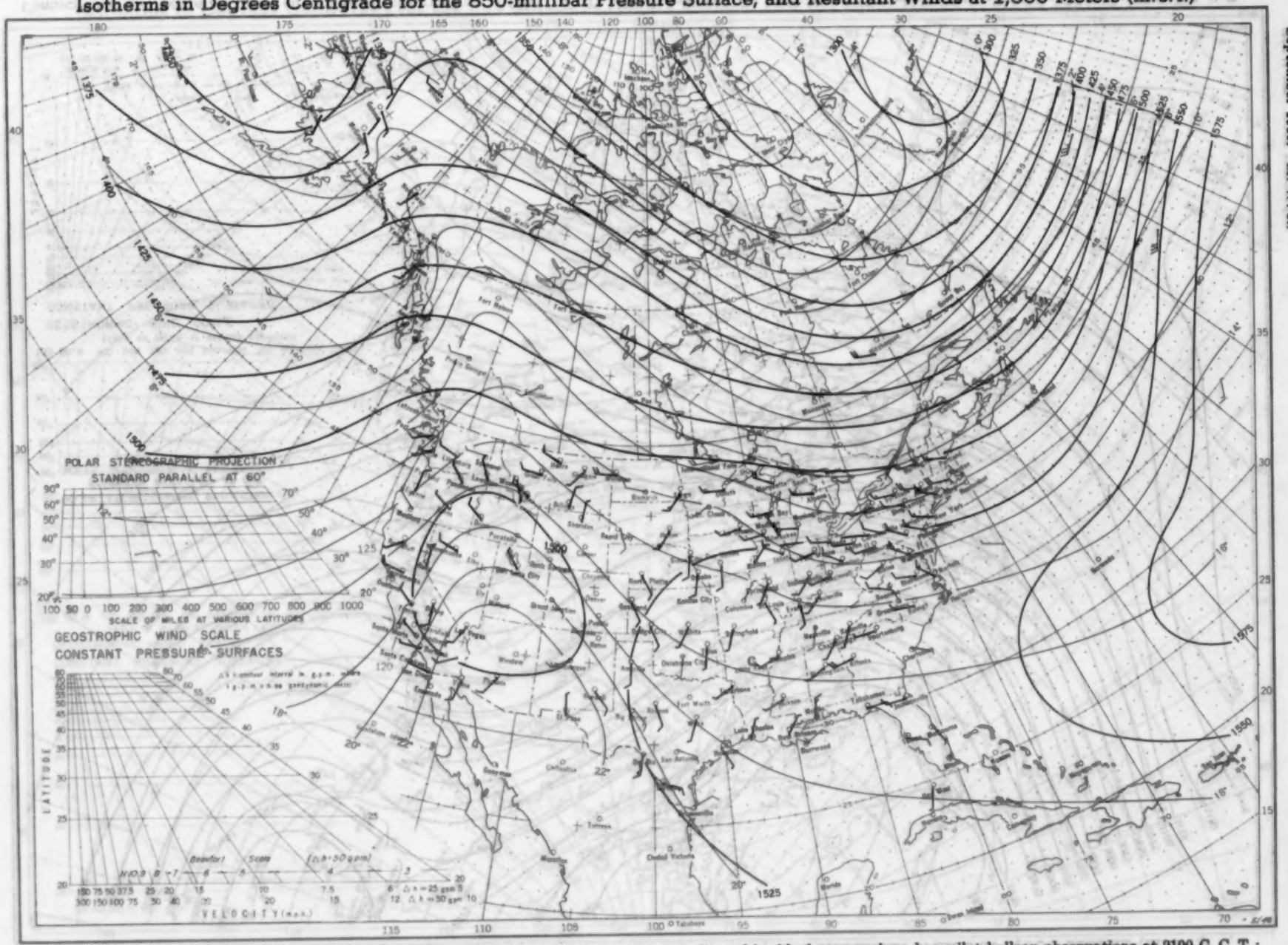
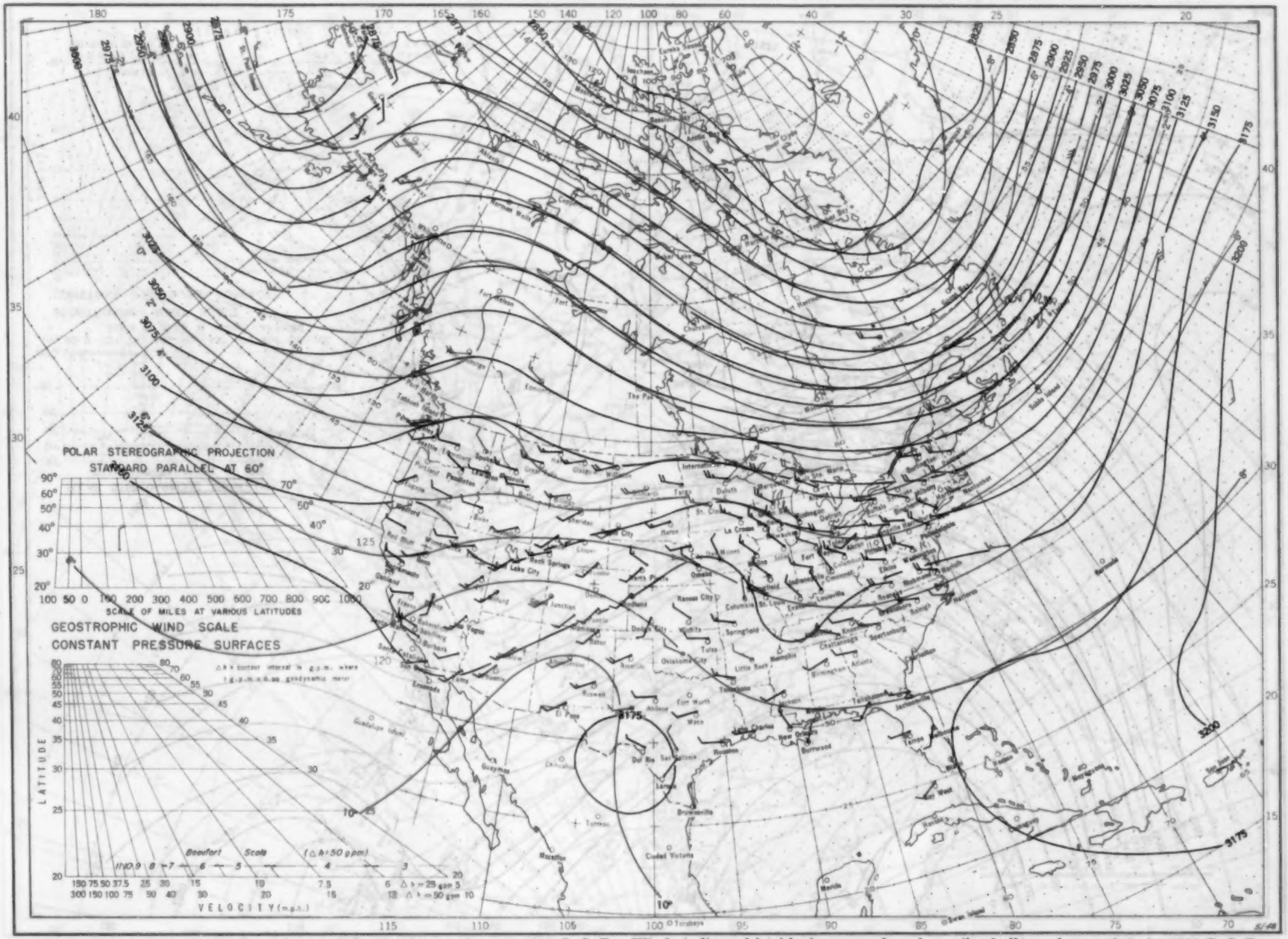


Chart VIII, September 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 850-millibar Pressure Surface, and Resultant Winds at 1,500 Meters (m. s. l.)



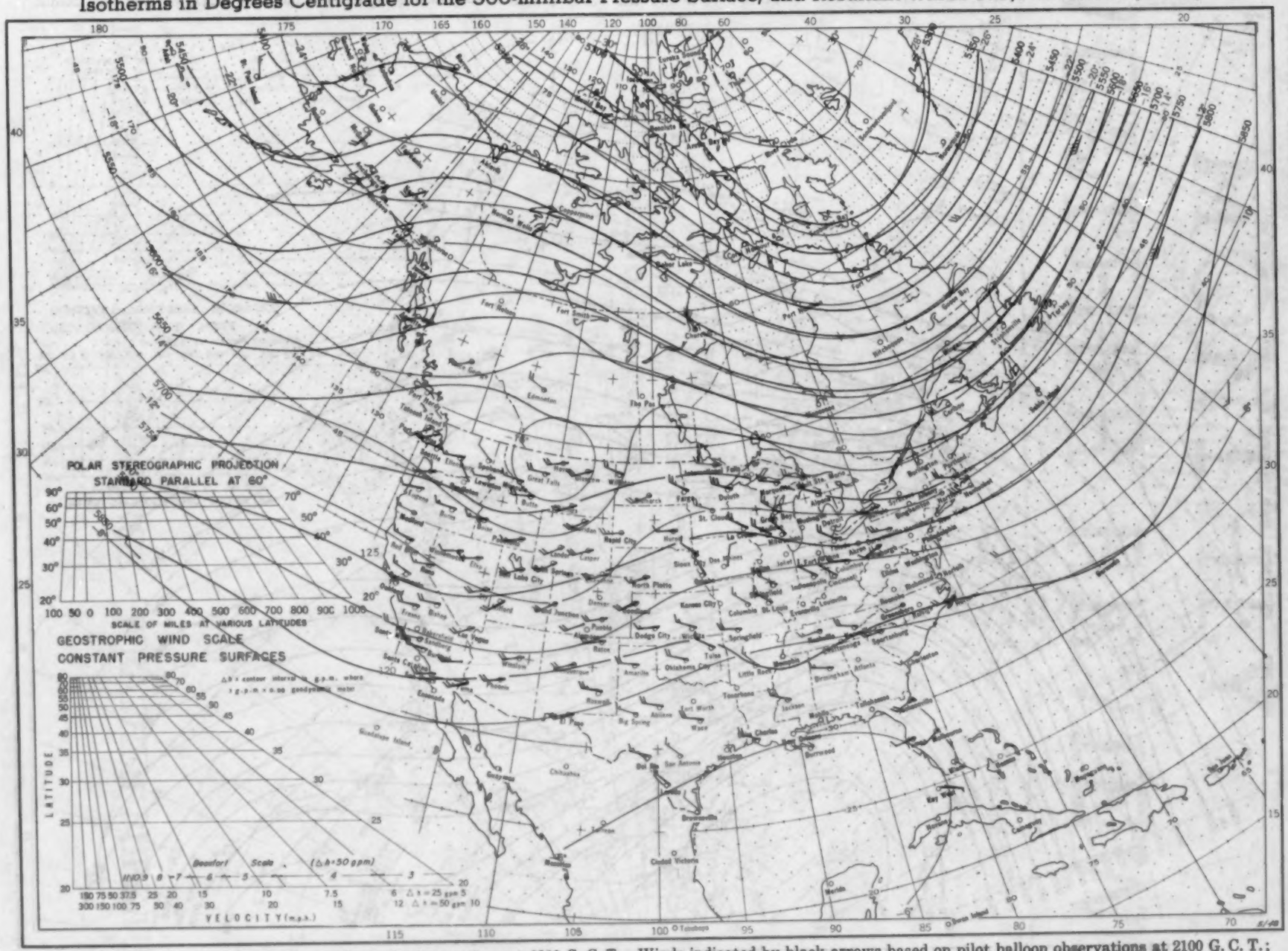
Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart IX, September 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 700-millibar Pressure Surface, and Resultant Winds at 3,000 Meters (m. s. l.)



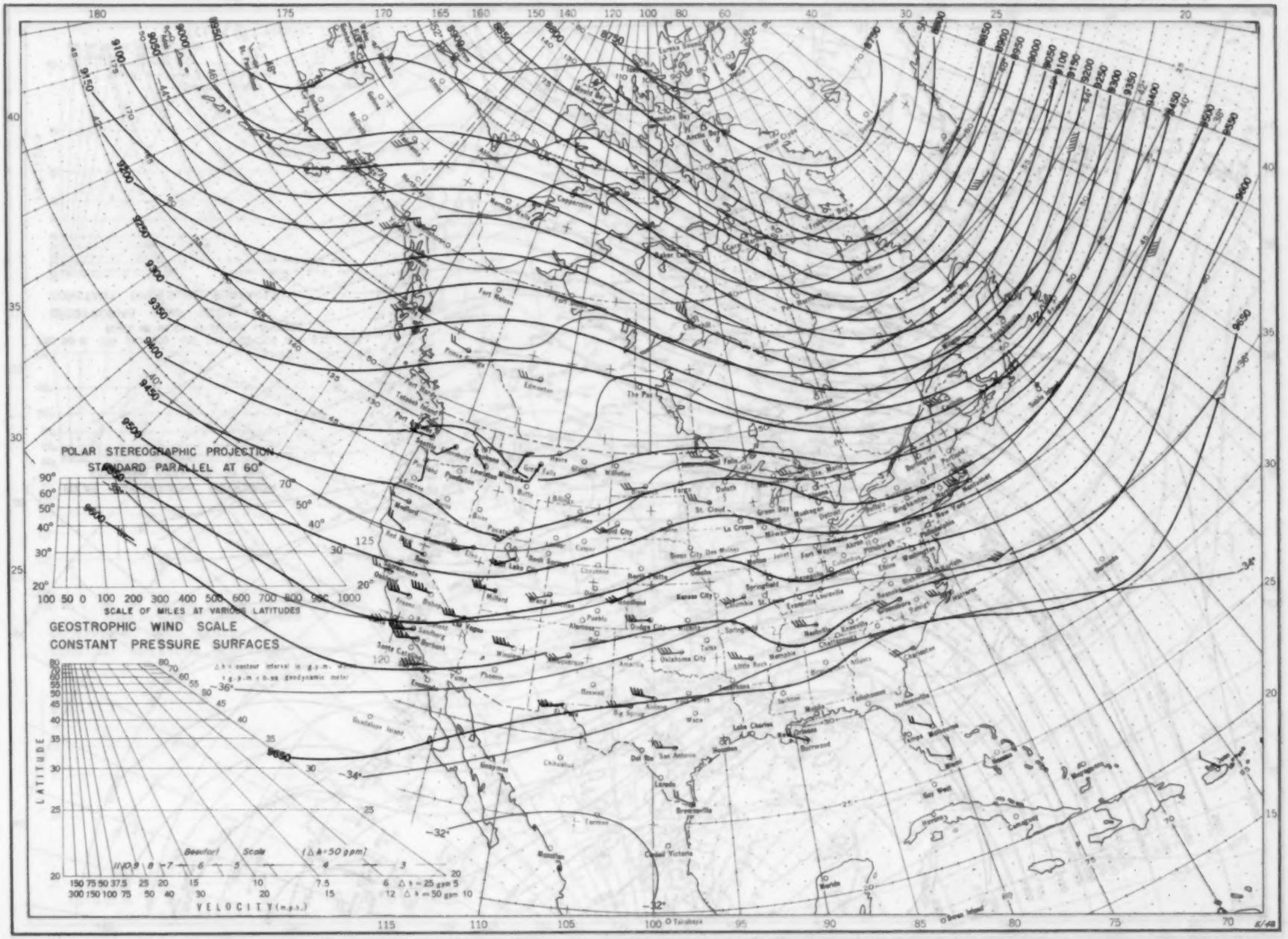
Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart X, September 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 500-millibar Pressure Surface, and Resultant Winds at 5,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart XI, September 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 300-millibar Pressure Surface, and Resultant Winds at 10,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.